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Mechanical Characteristics and Water Absorption Properties of Blast-Furnace Slag Concretes with Fly Ashes or Microsilica Additions

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Abstract: The paper shows the results of an experimental tests campaign carried out on concretes with recycled aggregates added in substitution of sand. Sand, in fact, has been totally replaced once by blast-furnace slag and fly ashes, once by blast-furnace slag and microsilica. The aim is both to utilize industrial by-products and to reduce the use of artificial aggregates, which impose the opening of pits with high environmental damage. The results show that in the concretes so made the water absorption capacity has reduced and durability has improved. The test campaign and the results described in the present article are certainly useful and can be especially utilized for research on a larger scale in this field.

Keywords: concrete; aggregates; fly-ash; silica fume; blast-furnace slag; mechanical properties; water absorption

1. Introduction

In recent times, the problem of preservation of reinforced and pre-stressed concrete structures has been developing rapidly. In fact, nowadays, as a consequence of the use of a bad mix design and inaccurate casting and execution of structures that occurred around the fifties, many structures present serious degradation phenomena. Moreover, there is a higher concentration of industrial and natural aggressive factors in the environment that can cause material degradation when compared to about forty years ago [1].

With a correct mix design, the appropriate use of super-plasticizers, low water/cement ratios, and, especially, the addition of materials constituted by very small granules obtained from the pozzolanic activity, it is possible to reduce the empty spaces in the particles of the concrete mix and get waterproof concretes with good mechanical strength characteristics.

The field of concrete technologies and its production is a current research topic. In recent years, recycling and re-use have become critical issues to develop concrete technologies and build reinforced concrete structures with a long service life and that, at the same time, are able to satisfy economic and environmental issues [2,3]. As a consequence, the use of industrial by-products or solid wastes in concrete production, such as fly ashes (FA), blast-furnace slag, and silica fume (SF) is increasing. Quite good mechanical properties, in fact, are obtained from concretes that use as aggregates calcareous rubble and, in total substitution of sand, blast-furnace slag [4].

Slag is constituted by scoriae at the liquid state; they remain in the furnace and are eliminated during the cast iron production. Approximately 300 kg of slag is generated per ton of pig iron.

In particular, the slag cools in extremely quickly and prevents the crystallization process. As a consequence, it solidifies in glass granules mixed with foamy fragments [5,6]. From this process it is possible to obtain the so-called granulated blast slag, an industrial by-product, which can be classified as waste [7], thus increasing problems associated with environmental pollution. Therefore, the aim of this study is to try to increase its possible uses, especially in the field of construction [8,9]. Due to its low iron content it can be safely used in the manufacturing of cement. Two types of blast furnace slag, air-cooled slag and granulated slag, are being generated from the steel plants. The color of granulated slag is whitish. The air-cooled slag is used as aggregate in road making, while the granulated slag is used for cement manufacturing. Although it has no behavioral problems, its use as aggregate in concrete is not very common and there has been little research work done on the subject.

The optimum cement replacement level with granulated blast-furnace slag is often quoted to be about 50% and sometimes as high as 70% and 80% to get an improvement of the mechanical and durability properties of concrete and to generate less heat of hydration.

On the other hand, concrete based on Portland cement is the most widely used material in the world. Compared to other materials like steel, aluminum and plastics, it is the most viable option for the construction industry considering economic and environmental costs. Nonetheless, it is estimated that 7% of anthropogenic CO_2 corresponds to the ordinary Portland cement production; considering the current global environmental situation, it is obvious that cement and concrete specialists must search for ways to reduce that figure, or at least to avoid its growth. One of the possibilities is the massive usage of industrial wastes like blast-furnace slag, to turn them into useful environmentally friendly and technologically advantageous cementitious materials [10]. In a previous study, the slag partially replaced 30%, 50% and 70% of Portland cement, and the cement's strength reduced as the amount of slag increased [11].

The use of blast-furnace slag on a large scale as a material to replace natural aggregates is a most promising concept because its impact strength is higher than that of natural aggregate. It is important in those areas where artificial aggregates are almost exclusively used. In this way, the crushing process of rocks, for example, which is commonly practiced in Apulia, Italy, would be reduced and consequently, the opening of new quarries—unfavorable in terms of environmental impact—would be reduced too [12].

To have the lowest possible environmental impact it is necessary to consider many aspects in the field of concrete technologies and in concrete production, such as the cost of construction and materials, its durability, and especially its compatibility with the protection of the environment. A solution to protect the environment is the use and/or re-use of industrial by-products or solid wastes to add to the concrete mix, such as fly-ash, blast-furnace slag, and silica fume [13].

In the literature, mortars and concretes added with different materials in the mix design have been studied and tested with the aim to improve their mechanical properties [14–16] and, at the same time, to reduce its environmental impact and the amount of waste sent to landfills [17–20]. The latter is especially due to their environmental friendliness and high durability properties. In Foti and Paparella [21], Foti [22], and Metha [23–25], alternative technologies for concrete production were considered by analyzing the cost of materials and construction, durability, and especially environmental friendliness.

Hefni et al. [26] used a high-volume of fly-ashes as a partial replacement of cement in concrete with the addition of different chemical activators and glass fibers and by investigating the concrete strength at room temperature and after exposure to elevated temperature. Usually, the slag in its original granulometric composition has very few fine granules [27]; hence, it is not possible to use slag in place of sand: the concrete so obtained would not be very compact and, consequently, very porous and with a very low strength. However, it is possible to fill the empty spaces with sieved slag made of very small granules; in this way the aggregates are rubble, original slag and sieved slag.

To obtain better performance it is possible to use fly-ashes instead of sieved slag. Fly-ashes, which are by-products of an industrial process (more precisely, of carbon combustion in power-stations), are constituted of very small granules with properties similar to those of the natural pozzolan. For this reason, fly-ashes can be used in partial replacement of cement or as aggregates of mortar, similar to sand, that is, the very thin fraction of the mix design [28,29].

However, the above considerations lead us to believe that an improvement is possible by adding to the slag, in its original composition, other materials made up of very fine particles that replace the sieved fraction. The so-called "fly-ashes" or "light ashes" are particularly suitable for this purpose. With the imported coals and the most commonly used boilers today, the residual ash as a whole is about 13% by weight of the starting fuel. Of this, a small part falls to the bottom of the combustion chamber in a special tank containing cooling water and forms the so-called "heavy" ashes. The remaining part, equal to about 85% of the total ash, follows the path of the gaseous combustion products that, by law, must be dedusted before being dispersed into the atmosphere. Without dwelling on the manner in which this process is implemented, it is sufficient to note that the so-called light ash obtained in this way is a very good quality fine material, with a composition and binding properties not very different from those of natural pozzolans. They are suitable to be used in partial substitution of cement, and as aggregates in concrete with sands poor in thin elements that have already been successfully tested.

An alternative is to replace fly-ashes with microsilica (silica fume), another artificial product obtained by the reduction process of quartzite during the production of alloys like iron-silicon or metallic silicon. Microsilica is constituted of granules smaller than fly-ashes. Their origin is from oxidation, hardening and condensation of silica fume at 2000 °C, following a process similar to the natural pozzolan [30]. Microsilica is utilized in many countries to make concretes with high durability [31]. They are composed of spherical granules with a diameter of 0.1 µm; this size allows the granules to fill all of the empty spaces of concrete. Microsilica is mainly comprised of dioxide of silicon; dioxide activates the transformation of hydrates of calcium (dangerous for concrete durability) in an insoluble, stable and effective product to fill all the pores. The inclusion of silica fume at high replacement levels significantly increases the autogenous shrinkage of concrete due to the refinement of pore size distribution that leads to a further increase in capillary stress and more contraction of the cement paste [32]. In fact, microsilica fume addition produces a positive influence on the dynamic and static mechanical properties of concrete, especially on the resonant frequencies, the dynamic and static moduli of elasticity, damping ratio and strength [33,34]. In particular, the results obtained by Giner et al. [28,29] evidence that microsilica additions or replacements reduce both the dynamic modulus of elasticity and damping ratio of concrete.

In other studies [35–37], some fibers (like carbon or steel fibers) were added to silica fume concretes, obtaining an improvement in the tensile and compressive strengths of concrete.

Bhanjaa and Senguptab [38], and Langana et al. [39] determined the influence of silica fume over a wide range of water-binder ratios and cement replacement percentages. In particular, the incorporation of blast-furnace slag into silica fume concrete reduces the water demand and this combination offers increased resistance to the alkali-silica reaction expansion and chloride ingress than the use of one of these materials alone [40].

Charlee et al. [41] and Elahi et al. [42] showed how the increase of fly-ashes replacement in concrete clearly reduces the chloride penetration (CP) and the steel corrosion in concrete. The last characteristic is also explained because these fine by-products make the microstructure of concrete denser, reducing its diffusivity [43,44].

In the present paper, the good results of experimental tests carried out on concretes in which sand is totally replaced by blast-furnace slag and microsilica, or by blast-furnace slag and fly-ashes are shown and discussed. Mechanical characterization tests and water absorption tests are performed. Blast furnace slag was integrated in the finest fraction by means of appropriate percentages of microsilica or fly-ashes. The tests, although preliminary by nature, confirm the possibility to obtain concretes with satisfactory mechanical properties and lower water absorption values using either fly-ashes or microsilica. Therefore, the results and comparisons reported in this paper are important bases towards the aim of carrying out wider research in this field.

2. Materials and Methods

A series of strength and water absorption tests were performed on specimens made with two different mixes:

(1) Concrete + slag + fly-ashes;
(2) concrete + slag + microsilica.

All tests were carried out at the Laboratory for Testings and Materials "M. Salvati" of the Polytechnic University of Bari, Italy. Different shape specimens were manufactured depending on the kind of test and the characteristics to be determined.

2.1. Materials

The specimens were manufactured utilizing two different mixes made of the following materials:

- High strength Portland cement (following the EC2 prescriptions [45]);
- Blast-furnace slag produced by the ILVA factory, Taranto, Italy (Figure 1a);
- Fly ashes coming from ENEL power station of Brindisi, Italy (Figure 1b); it is constituted on average by 90% of granules with dimensions smaller than 0.3 mm, by 60% of granules smaller than 0.04 mm, and by 10% of granules smaller than 0.01 mm;
- Microsilica of ELKEM MATERIALS a/s Kristiansand, Norway (Figure 1c);
- Calcareous rubble;
- Super-plasticizer RHEO-BUILD 1000 from MAC S.p.A.

(**a**) (**b**) (**c**)

Figure 1. (**a**) Blast furnace slag, (**b**) fly ash and (**c**) microsilica from Elkem utilized for the tests.

The characteristics of the materials and their chemical compositions were provided by the manufacturers; they are shown in Table 1.

Table 1. Properties and chemical composition of the materials utilized in the concrete mix.

	Cement (daN/m^3)	**Slag (daN/m^3)**	**Fly Ashes (daN/m^3)**	**Microsilica (daN/m^3)**
Absolute specific weight	3100	2720	2140	2160
Bulk density	1400	1110	700	737
Chemical Composition %				
SiO_2	17–25	30–40	40–55	88–98
Al_2O_3	2–8	6–18	20–30	0.5–3
CaO	60–67	38–50	3–7	0.1–0.5
MgO	0.1–5	2–6	1–4	0.3–1.5
SO_3	1–4.8	-	0.4–2	-
Na_2O	-	-	-	0.2–1.4
K_2O	0.2–1.5	-	1–5	0.4–1

The granulometric curve of the blast-furnace slag is shown in Figure 2.

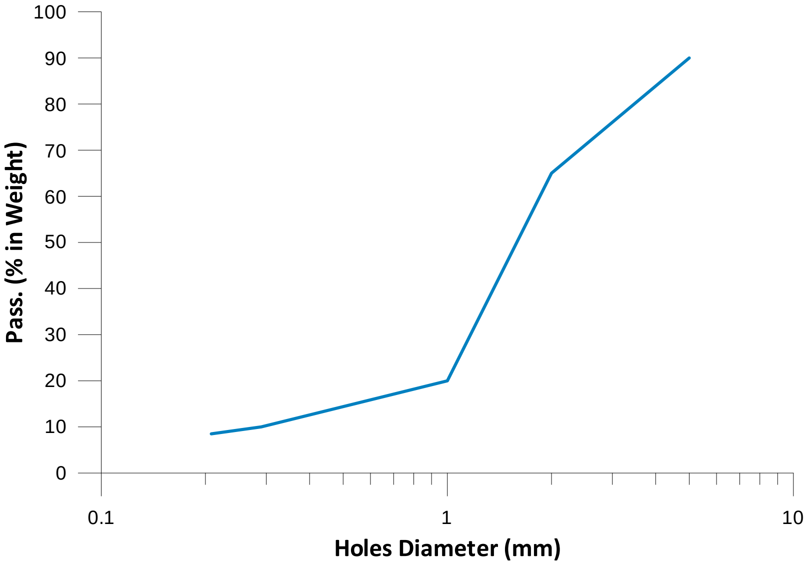

Figure 2. Granulometric curve of blast-furnace slag.

Calcareous rubble was utilized with two different granulometric curves represented in Figure 3. Kind A rubble was utilized in concretes with slag and fly-ashes; kind B rubble has been utilized for concretes with slag and microsilica.

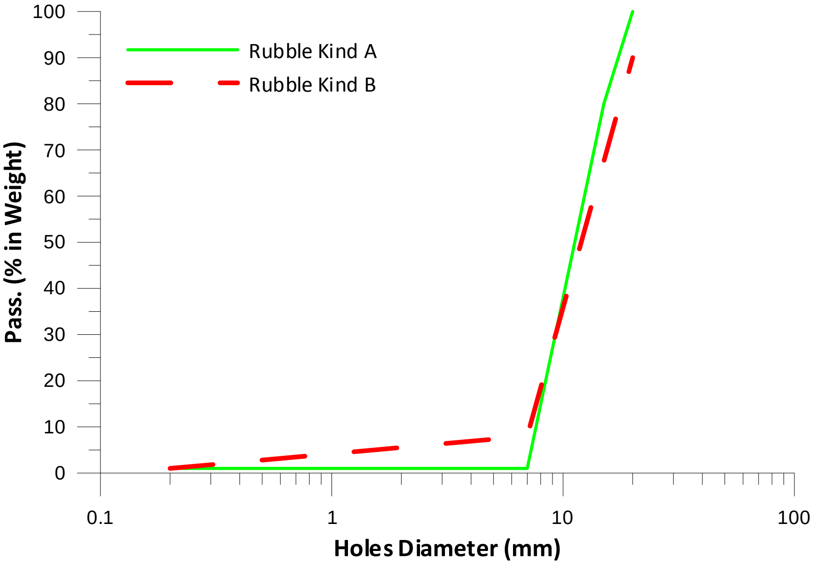

Figure 3. Granulometric curves of rubble.

2.1.1. Concretes with Slag and Fly Ashes (FA)

The concrete with slag and fly-ashes in total substitution of sand and rubble was realized with a calibrated percentage of the aggregates. Therefore, defining the maximum diameter of the aggregate and the consistency of concrete, the mix design was prepared to have a characteristic strength R_{ck} equal to 30 N/mm^2, following A.C.I., 1991 [46] and DOE, 1988 [47] prescriptions. In this case, by setting a maximum diameter of the aggregate equal to 20 mm, a "plastic" consistency and an average strength equal to the value previously assumed, it was possible to define the necessary quantity of water, the volume of blocked air, the water/cement ratio and the quantity of binder required [48].

The residual amounts of aggregates were finally fixed (rubble and slag), taking care that the characteristics of the latter did not allow to refer to a continuous type granulometric curve (Figures 2 and 3).

The composition of the aggregates was studied on the basis of the suggested criteria for discontinuous granulometries [49], which allows a quantity of about 700 N/mm^3 to pass through a 1 mm sieve. The test program takes into account that the slag has only 21% of granules of dimensions smaller than 1 mm and, vice-versa, concrete and fly-ashes have the size of all granules below it. In the end, the known volumes of water, cement, fly-ashes, slag, and blocked air, and the amount of rubble were fixed for difference. Then, the resulting composition was optimized by preliminary tests; the final composition with the ratios of the components that were assumed in the concrete mix is shown in Table 2.

Table 2. Composition of slag and fly ashes (FA) concrete mix per unity of volume and ratios of the components.

Rubble	Fly Ashes	Water	Slag	Cement	Super-Plasticizer
1080 daN/m^3	130 daN/m^3	220 L/m^3	522 daN/m^3	340 daN/m^3	4.7 L/m^3
Components Ratio					
water/cement	water/(ashes + cement)		ashes/cement	super-plasticizer/(ashes + cement)	
0.65	0.47		0.38	0.01	

The granulometric curve of the aggregates is shown in Figure 4.

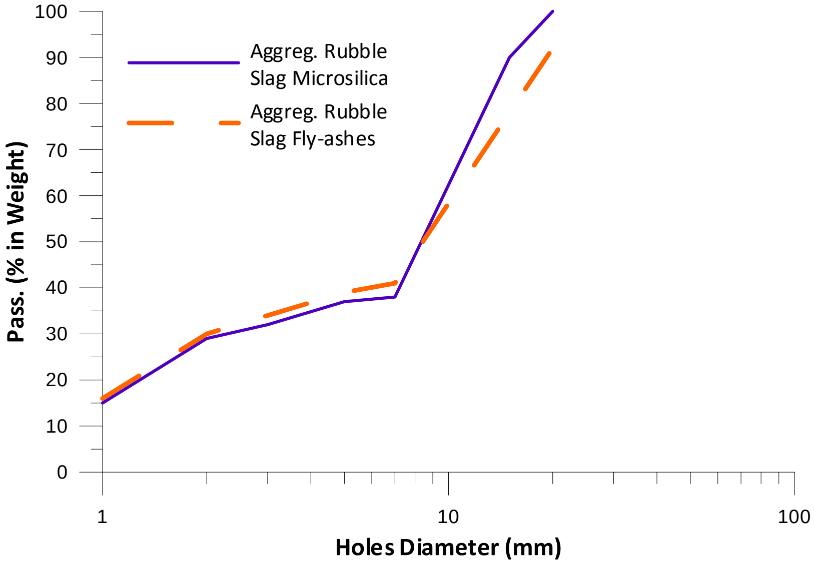

Figure 4. Granulometric curves of the aggregates of slag and FA concrete, and slag and SF concrete.

2.1.2. Concretes with Slag and Microsilica (SF)

In this case, the concrete with slag and microsilica was obtained by totally substituting the fly-ashes added to the previous concrete mix with an equal quantity of microsilica, whose characteristics are shown in Table 1. The preliminary tests also show the necessity to increase water and super-plasticizer to obtain a concrete with the same consistency and workability of the concrete of slag and fly-ashes previously described. The final composition of the mix is shown in Table 3.

The granulometric curve of the aggregates is also shown in Figure 4. Comparing the two concrete mixes, it is possible to notice that the two curves almost coincide for diameters smaller than 3 mm; that is the most significant field. The ratios shown in Table 3 have been assumed in the concrete mix.

Table 3. Composition of slag and microsilica (SF) concrete mix per unit of volume and component ratios utilized.

Rubble	**Microsilica**	**Water**	**Slag**	**Cement**	**Super-Plasticizer**
1080 daN/m^3	131 daN/m^3	296 L/m^3	522 daN/m^3	340 daN/m^3	7.22 L/m^3
Components Ratio					
water/cement	water/(microsilica + cement)		microsilica/cement	super-plasticizer/(microsilica + cement)	
0.87	0.63		0.38	0.015	

For comparison purposes, cubic specimens were manufactured with ordinary concrete (ORD); the control mix composition is shown in Table 4. It is a well cured and a high strength concrete (47 N/mm^2 at 28 days of curing). Like for slag and FA and slag and SF concretes, the quantity of water was assumed in order to get the same consistency and workability. In this case the ratio water/cement = 0.60.

Table 4. Composition of ordinary concrete (ORD) mix per unit of volume.

Rubble	**Sand**	**Water**	**Cement**	**Super-Plasticizer**
1080 daN/m^3	700 daN/m^3	204 L/m^3	340 daN/m^3	4.0 L/m^3

2.2. Test Methods

Strength tests and water absorption tests were performed on the specimens. The tests were carried out at the Laboratory for Testings and Materials "M. Salvati" of the Polytechnic University of Bari, Italy.

Three concrete specimens were manufactured for each strength test. Compressive, bending and traction tests up to failure were performed on the specimens. For the tests, 300 kN Metrocom equipment was utilized; for traction tests, an appropriate grip was manufactured, while the 3-point bending tests were performed by mean of an ad-hoc accessory for the machine. It was also determined that the compressive modulus of elasticity E after 28 days of curing, in the stress field 0–$\sigma_r/3$, where σ_r is the failure stress.

Water absorption tests were carried out on three cylindrical specimens for each type of concrete (with rubble, slag and fly-ashes and with rubble, slag and microsilica) in accordance with UNI 7699, 2005 [50]. In the test procedure, the specimens were dried in an oven at 100−110 °C for 24 h, and then their weights were measured. Next, the specimens were fully immersed in a water tank for 24 h, then they were taken out. Their surfaces were dried with a cloth and finally their weights were measured again. The test was conducted on the specimens with different curing ages (7, 14, 21, and 28 days).

2.3. Results

2.3.1. Strength Tests

Table 5 shows the average values of the failure stresses obtained after 7, 28, and 90 days of curing for slag and fly-ashes concretes. In this case, the compressive elastic modulus E, after 28 days of curing and in the stress field 0–$\sigma_r/3$ is equal to about 25,900 N/mm^2.

Table 5. Mean values and standard deviations of the mechanical characteristics of slag and fly ashes concrete.

Curing Days	**Specific Weight (daN/m^3)**	**Compressive Failure Stress (N/mm^2)**		**Flexural Failure Stress (N/mm^2)**		**Tensile Failure Stress (N/mm^2)**	
		Value	σ	Value	σ	Value	σ
7	2222	26.0	±3.74	-		-	
28	2185	36.5	±2.12	4.4	± 3.0	2.3	±3.61
90	2185	43.0	±3.74	-		-	

Table 6 shows the average values of the failure stresses after 7, 28 and 60 days of curing for slag and microsilica concretes. In this case, the compressive elastic modulus *E*, after 28 days of curing and in the stress field $0–\sigma_r/3$ is equal to about 25,140 N/mm^2. In Table 7 the mean values for compression strength of the different concretes are reported.

Table 6. Mean values and standard deviations of the mechanical characteristics of slag and microsilica concrete.

Curing Days	**Specific Weight (daN/m^3)**	**Compressive Failure Stress (N/mm^2)**		**Flexural Failure Stress (N/mm^2)**		**Tensile Failure Stress (N/mm^2)**	
		Value	**σ**	**Value**	**σ**	**Value**	**σ**
7	2140	31.2	±3.10	-		-	
28	2140	42.6	±5.724	3.3	±3.74	2.2	±1.73
60	2115	45.3	±4.32	-		-	
90	2113	47.1	±1.34	-		-	

Table 7. Compressive strength for the different concrete types.

Curing Days	**Ordinary Concrete (N/mm^2)**	**Slag and Fly Ashes Concrete (N/mm^2)**		**Slag and Microsilica Concrete (N/mm^2)**	
	Value	**Value**	**σ**	**Value**	**σ**
28	47	36.5	±2.12	42.6	±5.724

The methods utilized for the mix designs of the concrete utilized in the tests, appropriately refined by the preliminary tests, are shown to be good enough. However, it is evident from the results that the pozzolanic activity, both with fly-ashes, and especially with microsilica, played an important role in getting a good value for compressive strength.

The water/cement ratios are both quite high: if utilized to prepare an ordinary concrete, it would have been difficult to reach strength of the order of those obtained from the tests if there was no pozzolanic activity for fly-ashes and microsilica. Therefore, the ratios water/(fly-ashes + cement) and water/(microsilica + cement) are considered more significant in both cases.

The higher compressive strength obtained utilizing microsilica instead of fly-ashes is justified by the higher pozzolanic activity of silica fume and, especially, by the dimensions of their granules, which were much smaller than fly-ashes and typical of microsilica. The better behavior is obtained even if, when microsilica are used, it is necessary to add more water and super-plasticizers in order to obtain the same consistency as concrete with fly-ashes (see Table 3).

From the tests it seems that higher strengths are obtained for concrete with slag and microsilica, while the specific weight is a little lower than the weight of concretes with slag and fly-ashes. Moreover, for both concretes it seems that while the tensile strengths are comparable with the compressive strengths, the bending strengths are quite low, especially for concretes with slag and microsilica.

A similar result is obtained for the elastic longitudinal moduli, which are not very high if compared to the compressive strength, and lower than an ordinary concrete with the same compressive strength. The latter result is probably due to the discontinuous composition of the aggregates utilized and to the prevailing smaller fractions.

2.3.2. Water Absorption Tests

The percentage of water absorption by the different specimens was calculated from the following Equation (1):

$$\textit{Water absorption}\ (\%) = (\mathrm{Wi} - \mathrm{Ws})/\mathrm{Ws}\cdot 100 \tag{1}$$

where:

Wi = average weight of dry sample (g),
Ws = the average weight of the wet sample (g).

Table 8 reports the sizes of the specimens, their weights after curing, the weight increments during the phase of immersion in water (Figure 5), and the water absorption percentages (Figure 6). For the purpose of comparison, the results of the tests carried out on cubic specimens of ordinary concrete (well cured and with a high strength (47 N/mm^2)) are reported.

Table 8. Results of the absorption tests.

		Concrete of Slag and Fly Ashes			**Concrete of Slag and Microsilica**			**Ordinary Concrete (Ord)**		
	Specimens	1	2	3	1	2	3	1	2	3
	D × H (or L for cubic specimens) [mm]	96 × 96	96 × 96	96 × 96	96 × 96	96 × 99	96 × 92	10 × 10 × 10	10 × 10 × 10	10 × 10 × 10
	Weight after curing = Ms [N]	15.19	15.15	15.34	15.01	15.46	14.09	22.34	22.26	22.78
Weight increasing during the phase of immersion in water [N]	After 1 h	15.31	15.20	15.39	15.05	15.46	14.10	22.52	22.44	22.82
	After 3 h	15.74	15.63	15.73	15.25	15.92	14.41	22.81	22.72	23.08
	After 8 h	15.79	15.70	15.87	15.39	15.96	14.49	23.02	22.97	23.31
	After 24 h	15.80	15.71	15.88	15.45	16.01	14.53	23.40	23.30	23.75
	After 48 h	15.82	15.73	15.90	15.49	16.04	14.56	23.41	23.31	23.76
	After 72 h	15.83	15.74	15.91	15.51	16.05	14.57	23.42	23.31	23.76
	After 96 h	15.83	15.74	15.91	15.52	16.07	14.59	23.42	23.31	23.76
	After 120 h = Mi	15.84	15.74	15.92	15.53	16.08	14.60	23.42	23.31	23.76
	Absorbed Water [%] = W_{max} *	4.20	3.95	3.77	3.45	4.03	3.68	4.87	4.75	4.31

$$* \, W_{max} = \frac{100\,(M_i - M_s)}{M_s}.$$

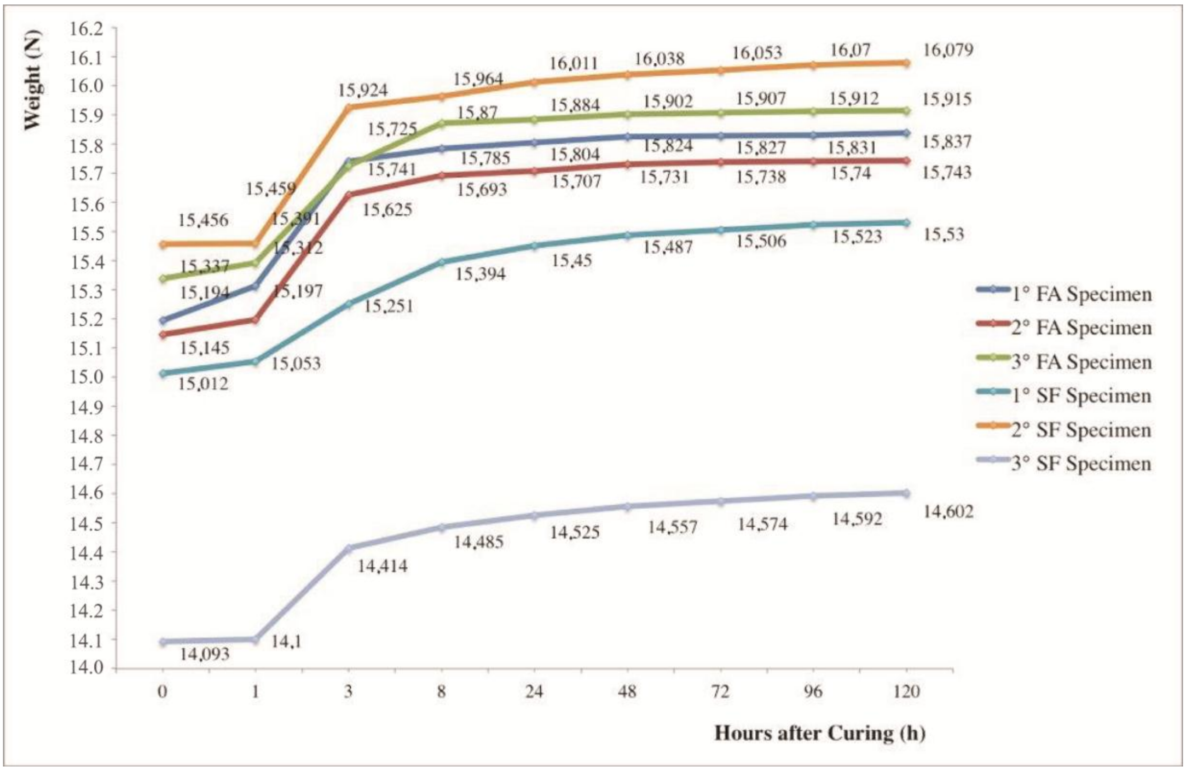

Figure 5. Weight increment during the phase of immersion in water of the specimens (FA = fly ash concrete and SF = silica fume concrete).

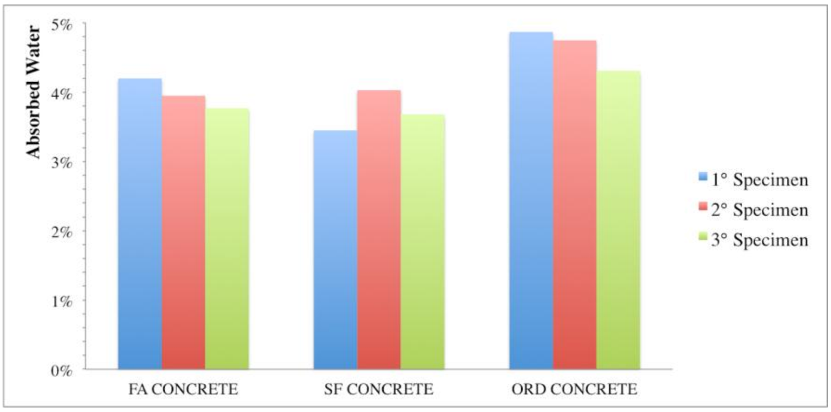

Figure 6. Percentage of water absorbed by the specimens.

For a clearer approach, Figures 5 and 6 show the curves and the histograms relative to the results of the water absorption tests. In Figure 5, h = 0 represents the time at which the immersion of the specimens in the water occurred.

The material porosity decreases both with the addition of fly ashes and microsilica fume. In fact, in the first case the reduction of total pore volume is probably due to the outcome of the continuous generation of pozzolanic reaction products from the hydration of FA that fill the pores. In the second case for microsilica fume concrete, the reduction of total pore volume is caused by the high pozzolanic reactivity, but also by the very small dimensions of SF particles and their pore-filling effect (they subdivide the pore space by amassing themselves between the cement grains).

Figure 6 shows the percentage of water absrbed by the different concrete specimens. It is possible to notice that the higher amount of absorbed water is obtained for the ordinary concrete specimens. In fact, the percentage of absorbed water with respect to the total weight is equal to 4.87% for an ordinary concrete, and 4.20% and 4.03% for FA and SF concretes, respectively.

2.4. Discussion

The overall results are presented in Tables 5–8 and they show that it is possible to obtain concretes with a very satisfactory mechanical strength and a low water absorption capability if sand is completely substituted with slag and fly-ashes, or with slag and microsilica.

The methods used to proportion the mix design, suitably refined through preliminary tests, have proved to be valid. From the results it is evident that the pozzolanic activity of fly-ashes, and especially silica fume, played a key role in reaching a very good compressive strength [51–53]. In fact, water/cement ratios are very high in both cases: these ratios, if utilized for an ordinary concrete mix without the pozzolanic activity of microsilica and fly-ashes, would have hardly given the same high strength values [54,55]. For this reason, it is worth considering the water/(fly-ashes + cement) and water/(microsilica + cement) ratios.

Higher compressive strength is achieved utilizing silica fume instead of fly-ashes [56]. In fact, it is known that the pozzolanic activity of concretes added with SF is higher with respect to other materials, as demonstrated also by Malhotra and Carette [57]. This is due to the higher pozzolanic activity and the smaller sizes of microsilica granules, even if more quantities of water and super-plasticizer are necessary to get the same consistency of fly-ashes concretes. In fact, the water/cement ratio from the value of 0.65 for concretes with slag and fly-ashes, reaches the value of 0.87 for concretes with slag and microsilica; the water/(fly-ashes + cement) ratio is 0.47, while water/(microsilica + cement) ratio is 0.63.

From the results of the tests it has been also possible to notice that microsilica concretes, apart from the higher mechanical strength, present a specific weight lower than for slag and fly-ashes concretes. Moreover, it seems that for both concretes the tensile strength is consistent with the compressive strength, while bending strength is rather low, especially for slag and microsilica concretes. Similarly, the longitudinal elastic moduli are not very high in comparison to the compressive strength and are lower than in an ordinary concrete of the same strength. It is probably due to the discontinuous composition of the aggregates utilized in the mix design and to the higher amount of mortar.

Finally, the water absorption test results showed that the mean values of water absorbed by the different concrete specimens were lower for slag and fly-ashes (or microsilica) concretes in comparison with ordinary concrete, and slag and microsilica concretes with respect to slag and fly-ashes concretes (Table 8, Figures 5 and 6).

In summary, these concretes that use by-products and scoriae of industrial production have mechanical properties comparable with a high strength ordinary concrete. Moreover, they show a lower water absorption capacity and a higher durability with the advantage to improve re-use and recycling of waste materials.

3. Conclusions

On the whole, the results obtained from the present study indicate that the methods utilized to proportion the mixes, appropriately refined through the preliminary tests, are valid. However, it is evident from the analysis of the results that the pozzolanic activity, both of the ashes and even more so of microsilica, played an important role in allowing the achieval of a good compressive strength, with the advantages of using concretes that re-use industrial by-products or solid wastes. Moreover, the two types of concrete, one in which sand is replaced by microsilica and the other in which sand is replaced by fly-ashes, are accurately compared, indicating precisely the pros and cons of each type with respect to their physical and mechanical properties.

The results obtained can be summarized as follows:

- The use of fly-ashes, and especially silica fume, together with slag in concrete enhances the compressive strength of concrete mixes and shows very high water/cement ratios.
- Microsilica concretes present a specific weight lower than slag and fly-ash concretes.
- For both concretes, the tensile strengths are consistent with the compressive ones, while bending strengths are rather low, especially for slag and silica fume concretes.
- Compared to an ordinary concrete, the types of concrete examined in this research have a lower water absorption value, especially the silica fume concrete.

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