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Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete

G.C. Isaia [*,1], A.L.G. Gastaldini [1], R. Moraes [2]

Rua Camelias, 175, 97020-120 Santa Maria, RS, Brazil

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Abstract

Pozzolans play an important role when added to Portland cement because they usually increase the mechanical strength and durability of concrete structures. The most important effects in the cementitious paste microstructure are changes in pore structure produced by the reduction in the grain size caused by the pozzolanic reactions pozzolanic effect (PE) and the obstruction of pores and voids by the action of the finer grains (physical or filler effect). Few published investigations quantify these two effects. Twelve concrete mixtures were tested in this study: one with Portland cement (control), nine mixtures with 12.5%, 25% and 50% of replacement of cement by fly ash, rice husk ash and limestone filler; two with (12.5 + 12.5)% and (25 + 25)% of fly ash and rice husk ash. All the mixtures were prepared with water/binder ratios of 0.35, 0.50, and 0.65. The compressive strength for the samples was calculated in MPa per kg of cement. The remaining contents of calcium hydroxide and combined water were also tested. The results show that the pozzolanic and physical effects have increased as the mineral addition increased in the mixture, being higher after 91 days than after 28 days. When the results for the same strength values are compared (35 and 65 MPa), it was observed that the filler effect (FE) increased more than the pozzolanic effect. The PE was stronger in the binary and ternary mixtures prepared with rice husk ash in proportions of 25% or higher.

Keywords: Mechanical strength; High-performance concrete; Mineral additions; Fly ash; Rice husk ash; Limestone filler; Calcium hydroxide; Combined water; Pozzolanic effect; Filler effect

1. Introduction

The utilization of pozzolans in combination with Portland cement to obtain high-performance concrete principally aims at improving concrete microstructure. According to Mehta and Aïtcin [9], the small particles of pozzolans are less reactive than Portland cement. When dispersed in the paste, they generate a large number of nucleation sites for the precipitation of the hydration products. Therefore, this mechanism makes the paste more homogeneous and dense as for the distribution of the finer pores, because of the pozzolanic reactions between the amorphous silica of the mineral addition and the calcium hydroxide produced by the cement hydration reactions. In addition, the physical effect of the finer grains allows denser packing within the cement and reduces the wall effect in the transition zone between the paste and the aggregates. This weaker zone is strengthened due to the higher bond between these two phases, improving the concrete microstructure and properties. In general, the pozzolanic effect (PE) depends not only on the pozzolanic reaction but also on the physical or filler effect of the smaller particles in the mixture.

Therefore, the addition of pozzolans to cement results in increased mechanical strength and durability when compared to the plain paste because of the interface reinforcement. Thus, the PE on the paste microstructure depends not only on the pozzolanic reactions but also on the filler effect (FE) of the finer particles. The physical action of the pozzolans provides a denser, more homogeneous and uniform paste. The replacement of 15% of the cement mass by silica fume will add approximately 2,000,000 particles to each cement grain

* Corresponding author.

E-mail address: gisaia@terra.com.br (G.C. Isaia).

[1] Professors of the Federal University of Santa Maria (UFSM), Santa Maria, Brazil.

[2] Student of the Master Degree Program of Civil Engineering at UFSM.

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replaced, as reported by Roy [10], in such a way that the fume particles surround each cement grain, densifying the matrix, filling the voids with strong hydration product, improving the bonding with aggregates, and reinforcing materials such as glass fiber.

Some researchers performed tests with non-pozzolanic fillers [2,3] to quantify their action on the increase of concrete strength. Goldman and Bentur [4,5] studied the effect of the addition of carbon black as micro-filler, and compared it to the effect of the addition of silica fume on the performance of high-strength concrete in pastes with *w/b* ratio of 0.46. These authors concluded that (Fig. 1): (a) the concrete with silica fume displayed higher strength values than the paste, while the opposite was observed in the paste without silica fume; (b) carbon black and silica fume effects were similar, because this concrete also displayed higher strength than the paste; (c) the comparative study suggests that the largest strength increase in the silica fume concrete is due to the micro-filler effect. This can be explained by the increased densification of the transition zone, which leads the aggregate to contribute effectively, to the strength increase to higher values than those in the paste; (d) the micro-filler effect is, at least, equally important or even more significant than the pozzolanic effect.

As Mehta [8] showed, the addition of fly ash or rice husk ash, whose particles are finer than those of Portland cement will, in most cases, cause a segmentation of larger pores and increase the number of nucleation sites for the precipitation of the hydration products of the cementitious paste. This will accelerate the reactions and form smaller calcium hydroxide crystals. The chemical action of the pozzolanic reactions enhances the physical effects because of the higher segmentation of pores and the refinement of CH grains as the curing time progresses. Berry [1] also detected that fly ash particles that are not completely reacted may fill the voids and increase paste density. This effect is more relevant as the fly ash content in the paste increases.

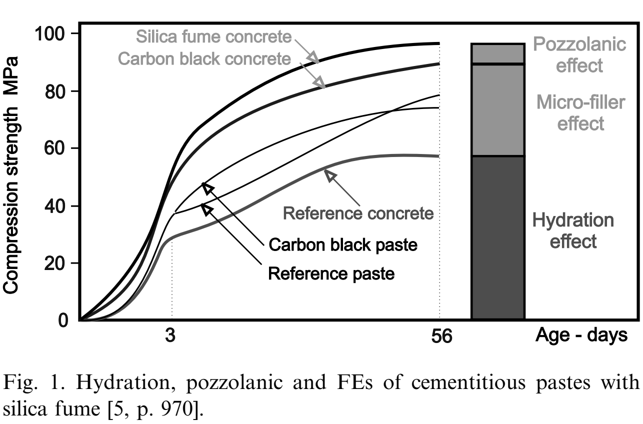

Fig. 1. Hydration, pozzolanic and FEs of cementitious pastes with silica fume [5, p. 970].

According to Isaia's [6,7] studies, when a less reactive pozzolan is employed in ternary mixtures together with another one more reactive such as silica fume or rice husk ash, there is a synergy between these pozzolans, thus the obtained result is higher than those verified in the respective binary mixtures; this result is called *synergic effect*. This fly ash effect may be explained by its physical effect, because it is related to the cement grain deffloculation provided by fly ash which is higher than that provided by silica fume or rice husk ash particles. This higher deffloculation increases the specific cement surface contacting water, being enhanced by the electrokinetic potential (zeta potential) between the particles. These mechanisms propitiate more quantity of nucleation sites to begin the hydration reactions, and the final result would be a higher amount of hydrated products and, consequently, higher calcium hydroxide consumption, pozzolanic activity and, finally, unitary strength gain (per mass unit of Portland cement in the mixture) or the enhancement of other variables linked with durability. The physical action enhances the chemical one, and the concrete global performance is increased.

Few studies recently published quantify the effects of these two actions upon the cementitious paste when part of the cement is replaced by pozzolanic additions. This work aims at quantifying the physical and PEs on binary and ternary mixtures of fly ash and rice husk ash in comparison with limestone filler, a mineral addition that is seen as an inert material for all practical purposes. Mixtures with increasing pozzolan contents at two different ages and strength levels were prepared to quantify these effects in relation to the amount of addition and strength threshold.

2. Experimental study

To reach the purposes of this research, an experimental laboratory study was developed using the following materials: high-early strength Portland cement; fly ash from a local power plant (Riocell); rice husk ash from a rice mill, ground for one hour; limestone filler from a local company, ground in the laboratory for one hour; naphthalene-based superplasticizer admixture; fine aggregate with Dmax = 4.8 mm and diabasic coarse aggregate with Dmax = 19 mm. Table 1 presents the physical and chemical properties of the cementitious materials.

The following concrete mixtures with fixed water/binder ratios of 0.35, 0.50 and 0.65 were prepared: reference (Portland cement), fly ash, rice husk ash and limestone filler with cement replaced by mineral addition of 12.5%, 25% and 50% per weight in binary mixtures; fly ash with rice husk ash in proportions of $(12.5 + 12.5)\%$ and $(25 + 25)\%$ in ternary mixtures. The lime-

Table 1
Physical and chemical characteristics of cement and mineral additions

	Cement	Fly ash	Rice husk ash	Limestone filler
Physical tests				
Specific gravity kg/dm^3	3.12	2.36	2.02	2.33
BET fineness m^2/kg	1800	3600	40100	5300
ϕ average of grains μm	8	9	11	4
Grains $\phi < 3$ μm%	26	19	13	46
Chemical tests (%)				
Loss of ignition	2.1	1.2	9.1	38.6
SiO_2	19.6	64.6	86.5	9.6
Al_2O_3	4.8	27.3	0.3	2.0
FeO_3	3.1	2.2	0.1	0.7
CaO	64.4	1.5	0.5	43.9
MgO	1.7	0.8	0.3	4.7
SO_3	2.8	0.1	0.1	0.3
Na_2O	0.1	0.2	0.1	0.1
K_2O	1.0	1.5	1.6	0.2

stone filler was used to compare its performance with the pozzolanic mixtures and allow the calculation of physical and PEs. The following tests were performed: axial compressive strength (NBR 5738) with 100 mm × 200 mm specimens; remaining calcium hydroxide content according to NBR 5748 and evaporable water content according to the guidelines of Sellevold and Justnes [11].

3. Investigation guidelines

The pozzolanic reactions depend on the calcium hydroxide released by the hydration reactions of calcium silicates. For this reason, they depend on Portland cement content in the mixture. Therefore, compressive strength, combined water and the remaining calcium hydroxide results were calculated in unitary terms, that is, as a function of the content of cement mass in each mixture.

For the sake of comparison, the reference Portland cement mixture was used, and unitary results were considered as a result of the hydration effect (HE). As Fig. 1 shows, the differences between the unitary strength of pozzolanic mixtures and the reference concrete were considered as the total effect (TE), that is, the sum of physical and chemical effects of the partial replacement of cement by pozzolans. The differences between the unitary strength of the limestone filler mixtures and the reference concrete were considered as a result of the FE. For practical purposes, FE was considered as a result of the physical effect of the inert limestone filler, as chemical interactions between the filler and the cement and pozzolans are minimal and can be discarded when compared to the magnitude of the other chemical reactions.

Considering the replacement of cement by mineral additions was carried out for the same mass and content both for pozzolans and the limestone filler, the overlapping principle was used to calculate the pozzolanic effect related to the total combined effect of the mixtures containing fly ash and rice husk ash. Consequently, for a given replacement content, the PE was calculated as the difference between the TE of the pozzolanic mixture and the FE of the respective limestone filler mixture, that is: PE = (TE − FE). If the unitary strength of the filler mixture is smaller than that of the reference concrete, the FE value is negative and PE will be higher than TE.

It is well known that the physical and pozzolanic effects operating on a given cementitious mixture are strongly dependent on both the pozzolanic activity of the pozzolan and its fineness. Although cement and mineral addition fineness in this study are quite different (see Tables 1 and 2), they were used in the grain sizes available in the market. This would allow this technology to be used without incurring high processing costs. Additional grinding to harmonize the grain sizes or change them into the same range of magnitude would add considerable costs and would reduce the benefit of these materials, that is, their low cost.

Since the concrete structures are calculated by setting a given strength level and, in most cases, this property is proportional to other durability-related variables, two strength levels were chosen to analyze the results. The first one (35 MPa) represents structures made with conventional concrete and the second one (65 MPa) represents high-performance concrete. Abrams' equations were calculated to correlate compressive strength to *w/b* ratios and to determine their specific values for both strength levels selected. Only in a few cases an extrapolation outside the test-result range was accomplished to obtain the desired strength level.

Table 2
Mixture proportions and test results

w/b	MA (%)	Mixture proportions (kg/m^3)						f_c (MPa)		CW (%)		CH (%)	
		PC	FA	RHA	LF	Water	Adm.	28 days	91 days	28 days	91 days	28 days	91 days
0.35	0	489				161	9.8	64.0	68.8	10.7	12.1	10.0	10.4
	12.5	428	61			161	9.8	70.7	80.0	8.3	9.1	8.1	6.9
	25	367	122			152	19.6	63.9	70.8	8.7	8.8	6.6	5.8
	50	244	244			131	38.9	55.3	62.7	8.0	9.0	1.5	0.9
	12.5	428		61		157	14.7	68.4	73.2	9.5	10.0	8.6	7.1
	25	367		122		147	24.5	75.6	79.4	10.3	11.5	5.8	4.3
	50	244		244		127	48.9	44.3	69.5	10.9	12.7	0.3	0.1
	12.5	428			61	163	11.0	51.9	68.9	9.7	10.5	10.8	10.0
	25	367			122	164	8.6	48.7	56.7	7.0	7.5	10.0	9.3
	50	244			244	152	4.9	32.9	39.3	6.1	6.6	8.2	7.4
	25	367	61	61		152	19.6	59.5	78.8	7.6	9.2	2.8	2.1
	50	244	122	122		142	29.4	65.9	72.0	9.5	10.4	1.0	0.7
0.50	0	359				178	1.8	47.8	52.2	10.8	13.6	12.8	13.3
	12.5	314	45			177	2.7	43.8	50.0	8.9	12.0	9.4	7.7
	25	270	90			169	10.8	45.7	49.1	9.9	11.2	7.4	6.3
	50	180	180			162	18.0	30.5	357	8.3	9.4	2.6	1.8
	12.5	314		45		176	3.6	39.0	49.3	10.6	10.6	9.9	8.0
	25	270		90		169	10.8	53.1	61.1	10.6	12.2	6.5	5.0
	50	180		180		160	19.8	35.5	52.7	11.0	12.7	0.7	0.3
	12.5	314			45	178	1.8	37.0	48.9	10.5	11.2	12.6	10.9
	25	270			90	178	1.8	31.8	35.3	8.2	9.1	11.4	10.2
	50	180			180	180		20.7	24.8	6.3	7.0	9.0	8.5
	25	270	45	45		179	1.8	37.8	51.1	8.6	11.3	3.2	2.6
	50	180	90	90		174	5.4	45.7	46.9	9.7	12.2	1.5	1.1
0.65	0	284				185		33.4	34.8	1.9	14.5	13.3	14.0
	12.5	249	35			185		35.5	40.0	10.0	12.5	10.8	9.1
	25	214	70			180	2.1	31.1	35.6	10.7	12.0	9.2	7.5
	50	140	140			179	5.7	20.6	26.9	8.5	9.6	3.1	2.2
	12.5	249		35		185		30.9	35.1	10.7	10.9	11.7	9.8
	25	214		70		183	1.4	35.1	42.8	10.9	12.6	7.2	5.3
	50	140		140		178	7.1	22.9	30.1	11.4	13.4	1.0	0.4
	12.5	249			35	185		23.5	29.5	11.2	11.4	13.2	12.7
	25	214			70	184	0.7	19.3	20.1	9.8	10.6	12.0	11.0
	50	140			140	182		11.5	12.7	6.7	7.6	9.8	8.9
	25	214	35	35		183		22.9	31.7	9.9	13.2	5.5	3.4
	50	140	70	70		183	1.4	29.1	30.7	10.0	15.9	2.0	1.4

Keys: *w/b* = water/binder ratio, kg/kg; MA = mineral additions; PC = Portland cement; FA = fly ash; RHA = rice husk ash; LF = limestone filler; Adm. = admixtures (superplasticizer); f_c = axial compressive strength; CW = combined water; CH = remaining calcium hydroxide.

4. Discussion of results

4.1. Unitary compressive strength

The relationships between unitary compressive strength and the physical and chemical effects involved in the formation of resistant materials in the cementitious paste should take into account their interaction with the content changes in combined water and remaining calcium hydroxide from the hydration reactions. Figs. 2 and 3 show the correlations between unitary compressive strength (MPa/kg of cement) and the respective unitary contents of combined water and calcium hydroxide (%/kg of cement). It is observed that the calculated correlation coefficients are high, thus demonstrating a strong statistical correlation between these variables. In Fig. 2 the straight lines for 91 days are less inclined than those for 28 days. This indicates that higher water content to reach a given strength level shall be higher at 91 days than at 28 days, although these increases are smaller for higher strengths. In fact, for a unitary strength threshold of 0.20 MPa/kg, it is necessary to increase the combined water content by 3.7% to reach the 35 MPa strength level, while for 65 MPa, only 0.6% is necessary when the age of concrete increases from 28 to 91 day. This fact shows that for higher strength levels and lower porosity degrees, both the unitary content of combined water and the ΔCW (dif-

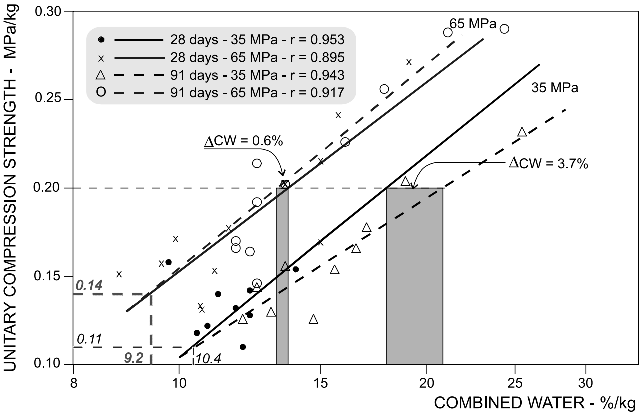

Fig. 2. Correlations between unitary strength and unitary combined water.

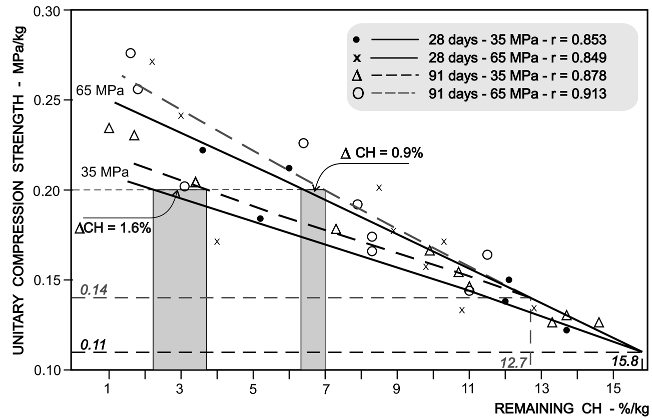

Fig. 3. Correlations between unitary strength and unitary remaining calcium hydroxide.

ferential increase of combined water) are smaller, indicating that higher strength levels are reached at the expense of the physical and/or pozzolanic effects rather than the cement hydration effects, that is, the proximity of cement particles is so important as the amount of hydrates that are formed.

Fig. 2 also shows the straight lines correlating the ages of 28–91 days for the 35 MPa strength level. For this strength, they intersect at a point determined by the coordinates (0.11, 10.4), and for 65 Mpa, at the coordinates (0.14, 9.2), suggesting that these figures are the lowest values that the cementitious paste should have, at any age, to reach the respective desired strength thresholds. So, in order to obtain a given strength level, there must be a certain amount of cementitious material and a specific porosity (due to *w/b* ratio), with a hydration degree providing the lowest unitary strength, that is, per unit of cement content in the paste. Without these conditions, the desired strength level in real magnitude will be not reached.

Similarly, Fig. 3 shows the same effects in Fig. 2 for the calcium hydroxide unitary content. However, some differences can be seen. For the 65 MPa strength level, the required unitary strengths are higher than those necessary for 35 MPa, which implies more inclined straight lines for the higher strength level than for the lower. The same is seen in relation to both ages. To obtain the same unitary strength level of 0.20 MPa/kg, the unitary CH increase is 1.6%/kg to reach a strength level of 35 MPa when the age rises from 28 to 91 days, and only 0.9%/kg, for 65 MPa. This behavior also suggests that, to reach higher strengths, the remaining calcium hydroxide content is higher, although the ΔCH increments are smaller when the age rises from 28 to 91 days. This shows that the growth in strength is more related to the physical effect than to the chemical one (hydration or action of pozzolans), as seen above.

Fig. 3 also shows the same behavior in the convergence of the straight lines for the same age and different strengths. The straight lines of both strength levels cross at coordinates (0.11, 15.8) for 28 days and (0.14, 12.7) 91 days. These are exactly the same unitary strength ordinates seen in Fig. 2 in relation to the combined water content. It seems that the above explanation is consistent, since, in order to obtain a specific strength level at a given age, it is necessary to reach a minimum unitary strength threshold with a given volume of resistant cementitious material, via hydration, pozzolanic or physical processes. The present data show that the minimum unitary content of CH (15.8%/kg) is higher for 28 days than 91 days (12.7%/kg), regardless of the strength level to be reached. This shows that, at higher ages, the remaining CH content is smaller due to its consumption by pozzolanic reactions.

The mechanisms described here show that to obtain the desired mechanical strength at a given age, when using cement with mineral additions, it is necessary to have a compatible combination of minimum amounts of solid material per volume units of Portland cement paste. This can be accomplished by means of hydration reactions (combined water), pozzolanic reactions (calcium hydroxide consumption) or the physical action of the reduced porosity resulting from smaller *w/b* ratios or the refinement of pores and grains of the cementitious material. Therefore, a hybrid, combined and synergistic action among these three effects is necessary: hydration, pozzolanic and physical effects. It is necessary to provide the paste with a given minimum unitary strength to reach the desired strength level.

4.2. Pozzolanic and physical effects

Fig. 4 shows the differences between the unitary results of the mineral additions and the reference concrete (TE) for both strength levels and ages. It is observed

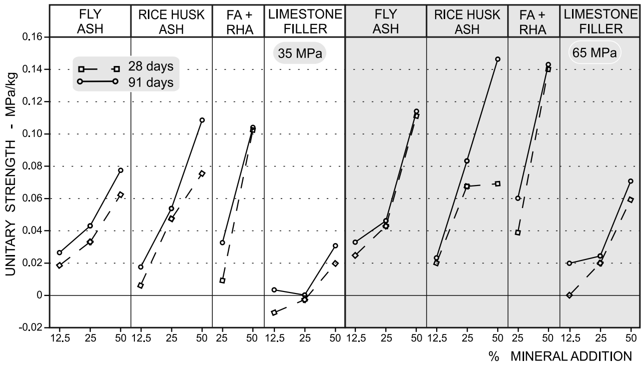

Fig. 4. Differences between unitary strength of pozzolanic mixtures and reference ones.

that the strength increase is higher for 91 days than 28 days, as expected, and the 65 MPa concrete displayed values higher than the 35 MPa samples. For all mineral additions used, the increases were significant as the replacement content in the mixture increased.

Figs. 5(a) and (b) present the same results as Fig. 4, individually showing the total, pozzolanic and filler effects. In most cases, the FE was the lowest, increasing

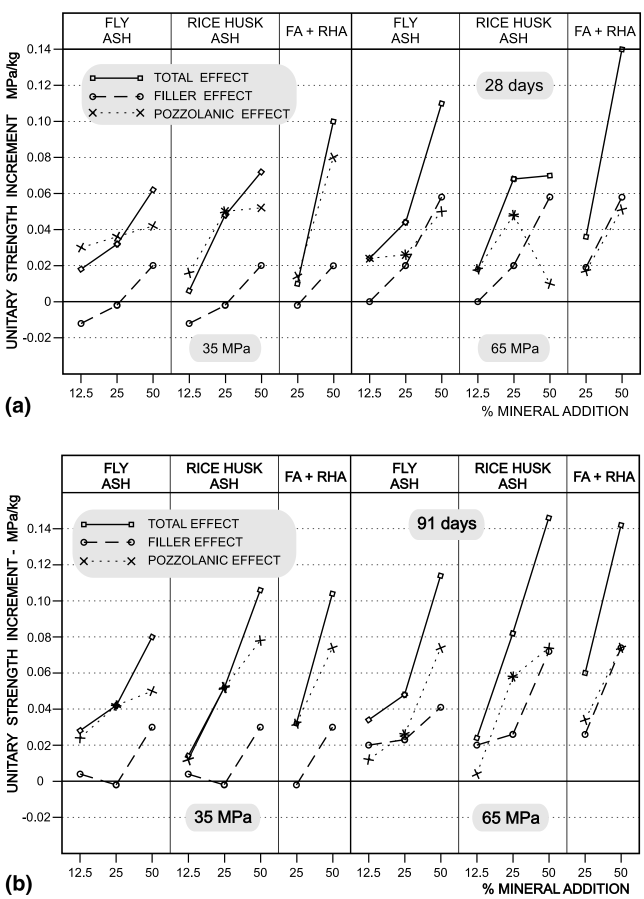

Fig. 5. Total, filler and pozzolanic effects at ages of 28 day (a) and 91 day (b) unitary compressive strength of mineral addition mixtures.

more significantly with higher strength levels than with the age. TE and PE 0were very similar for the 35 MPa level, but they diverged for the 65 MPa strength level. The PE decreases for higher strengths to the detriment of the FE. Only the 50% rice husk ash mixtures presented results somewhat erratic. This was probably due to the high admixture content that was necessary to reach the desired consistency.

Relative comparisons between these effects in Fig. 6(a) show average performances of the physical and PEs of the mixtures in relation to the reference concrete (used as reference index = 100), for the ages of 28 and 91 days. It can be seen that: (a) for both ages, the physical effect presented, on an average, an index of 114. The PE showed 131, a 17% increase when compared to the former; (b) the FE indexes increased, on average, from 110 to 118 (+8%) from 28 to 91 days, while the PE increased from 128 to 134 (+6%); (c) both the FE and the PE indexes increased with the increase in mineral addition content in the mixture as the age increased. When the addition content grew from 12.5% to 50%, the physical effect increased from 102 to 134 (+32%), while the PE went up from 120 to 145 (+25%).

Although the PE values were nearly always higher than those of the FE, the differences decrease when the age increases from 28 to 91 days and when the pozzolan content in the mixture rises. In some cases, such as those mixtures with 50% of fly ash or rice husk ash in binary

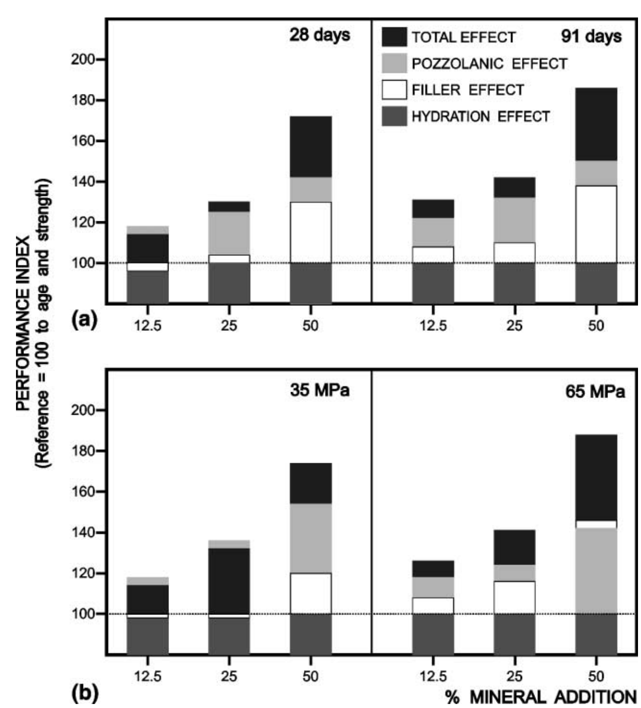

Fig. 6. Total, filler and pozzolanic effect performance indexes related to reference concrete at 28 and 91 days (a), 35 and 65 MPa strength levels (b).

mixtures, the FE value exceeded that of the PE, both for 28 and 91 days.

Fig. 6(b) shows the behavior of the mixtures for 35 and 65 MPa strength levels when compared to the reference Portland–cement mixtures (index = 100). It can be noted that: (a) on average, the physical effect displayed indexes equal to 106 and 125 (+19%) and the PE had indexes of 135 and 130 (−5%), respectively, for 35 and 65 MPa strengths; (b) the age increase from 28 to 91 days did not cause significant increments for both strength levels, which were, on average, 7% for both FE and PE effects; (c) when the amount of pozzolans increased from 12.5% to 50%, the physical effect indexes increased from 97 to 121 (+24%), for 35 MPa, and from 107 to 147 (+40%), for 65 MPa, while the PE caused growth from 117 to 151 (+34%) and from 124 to 140 (+16%); (d) for the FE, the mixtures with 12.5% of pozzolans presented increments of 10% when strengths went up from 35 to 65 MPa. For the 50% mixtures, this increase was 26%; (e) for the PE, the 12.5% pozzolanic mixtures presented a 7% strength increase, when the threshold went up from 35 to 65 MPa and a −9% decrease, for the 50% mixtures.

The above data reveal that the increase in strength levels benefits more the filler than the PE, although the latter is higher for lower strengths (35 MPa) and for lower mineral addition contents (12.5% and 25%). When the strength level increased to 65 MPa and the mineral addition content grew to 50%, a higher increase of the FE was observed, compared to the pozzolanic one, whose value actually dropped.

Fig. 7 compares the relative performance of fly ash and rice husk ash binary and ternary mixtures as for the reference mixture ($I = 100$): (a) the physical and pozzolanic effects, respectively, presented average indexes of 114 and 126 (+12%) for fly ash, 114 and 135 (+21%) for rice husk ash, and 120 and 139 (+19%) for the (FA+RHA) ternary mixtures; (b) when the strength level increased from 35 to 65 MPa, the physical effects for the fly ash and rice husk ash mixtures increased from 105 to 123 (+18%), and for the ternary mixtures, from 109 to 131 (+22%), while for the PE, they dropped, respectively, from 130 to 121 (−9%) for the first ones, from 135 to 134 (−1%), for the second ones, and from 141 to 137 (−4%) for the third ones; (c) as the pozzolan content increased from 12.5% to 50%, the physical effects rose by 32% for the fly ash and rice husk ash mixtures, and by 21%, for (FA+RHA). The PEs rose by 18% for the two first ones and 40% for the latter.

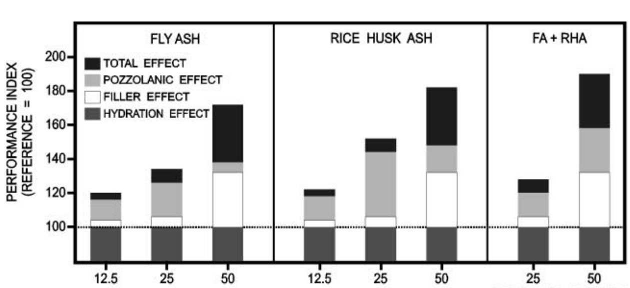

Fig. 7. Total, filler and pozzolanic effects performance indexes related to the reference concrete, binary and ternary mixtures.

These results indicate that for the investigated pozzolans, the pozzolanic and physical performance indexes showed a growing trend for fly ash and rice husk ash, with higher values for both ternary mixtures. The higher growth in unitary strength was obtained for the latter, by 50% (ternary mixtures). This shows that there is greater synergy (synergic effect) between the fly ash and the rice husk ash, when high contents are present in the ternary mixtures, as previously reported by Isaia [6].

5. Conclusions

When part of the Portland cement is replaced by fly ash, rice husk ash or limestone filler, each of these mineral additions operates in a different but co-operative way, according to its particle size and chemical or physical activity, concerning its interactions with the cementitious paste. From the results of this experiment, it is possible to conclude the following:

(a) The correlations between unitary compressive strength, unitary calcium hydroxide and unitary combined water contents show that when concrete has to reach a given level of compressive strength, it is necessary to achieve a minimum unitary strength with a given minimum content of combined water and/or remaining calcium hydroxide. In the present research, these values were: for 35 MPa strength level at 28 days, 0.11 MPa/kg unitary strength, 10.4% combined water content and 15.8% remaining calcium hydroxide content; for the 65 MPa strength level at 91 days, 0.14 MPa/kg, 9.2%/kg and 15.8%/kg, respectively.

(b) The previous finding suggests that there must be a minimum amount of resistant material per unit volume of cement paste to reach a given compressive strength level. This may be achieved by means of hydration reactions (combined water), pozzolanic reactions (calcium hydroxide) or even by the physical action caused by the smaller water/binder ratio or pore and grain refinement through a blocking or filling effect of the finer particles.

(c) The unitary compressive strengths increased sharply as the pozzolan content in the concrete mixtures did. On average, they grew from 22%, for 12.5% addition content, to 79%, for the 50% addition content, when compared to the reference mixture. The physical effect contribution to these values was less

significant (+2% and + 34%, respectively) than that of the PE (+20% and +45%, respectively).
(d) When the strength level increased from 35 to 65 MPa, the unitary strength increments were, on average, 42% for the former and 55% for the latter. Smaller but growing values for the FE, 6% and 25%, respectively, and falling values, 36% and 30%, respectively, for the PE were verified when compared to the reference concrete.
(e) For the ages of 28 and 91 days, the unitary strength increases were similar to those verified for compressive strength.
(f) On average, the PE was more significant in the lower-strength concrete mixtures (35 MPa) at a higher age (91 days), while the FE was more significant in the higher strength concrete mixtures (65 MPa), also for the age of 91 days.
(g) For mixtures containing 50% pozzolan and 65 MPa strength, the values obtained for the physical effect exceeded those of the pozzolanic effect, both at 28 and 91 days.
(h) The binary mixtures of rice husk ash showed better performance than the fly ash material, although the ternary mixtures have reached better overall results.
(i) The unitary strength values of the ternary mixtures show that the combination of a less active pozzolan, such as fly ash, with a more reactive one, such as rice husk ash, produces a synergistic effect in relation to the respective binary mixtures. This effect is higher as the pozzolan content in the mixture and the concrete strength level increase.

The results of this research evidenced the existence of a hybrid, combined and synergistic action between the hydration effect of the Portland cement (reference concrete), the pozzolanic action (chemical/physical effects) and, mainly, the FE (physical effect) upon the behavior of the unitary compressive strength when compared to Portland cement mixtures.

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