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Assessment of the influence of the type of aggregates and rehydration on concrete submitted to high temperatures

Avaliação do tipo de agregado e da reidratação Do concreto submetido à elevadas temperaturas

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Abstract

The behavior of concrete under fire is being studied by a group at the Structures and Civil Engineering Laboratory of the Civil Engineering, Architecture and Urbanism College in UNICAMP. This work presents an investigation on the loss of mechanical strength of different concrete mixes after submitted to high temperatures and on the influence of rehydration. Mixtures were prepared with three different aggregates: expanded clay, basalt and limestone. Test bodies were submitted to temperatures of 300 ºC and 600 ºC under the same heating rate as that of Curve ISO-834 (1999). After heat treatment, some of the test bodies were rehydrated in air, some were immerged in water and others were wrapped up in plastic film during 28, 56 and 112 days. At these ages, concretes were evaluated in relation to compression strength, tension strength and modulus of elasticity, therefore providing an assessment of the influence of the aggregate type and rehydration on the recovery of mechanical strength.

Keywords: concrete, high temperatures, mechanical properties, rehydration .

Resumo

O efeito do comportamento do concreto perante o fogo está sendo estudado por um grupo formado no Laboratório de Estruturas e Construção Civil da Faculdade de Engenharia Civil, Arquitetura e Urbanismo da UNICAMP. Este trabalho apresenta uma investigação sobre a perda de resistência mecânica ocorrida em diferentes misturas de concreto depois de submetidas a temperaturas elevadas, bem como, uma investigação da influência da reidratação. As misturas foram preparadas com três diferentes agregados: argila expandida, basalto e calcário. Os corpos-de-prova C, obedecendo a mesma taxa de 300 ºC e 600 ºC foram submetidos às temperaturas de 300 aquecimento da Curva ISO-834 (1999). Após o tratamento térmico, parte dos corpos-de-prova foram reidratados ao ar, outra parte foi imersa em água e outros envolvidos em filme plástico durante 28, 56 e 112 dias. Nestas idades os concretos foram caracterizados em relação à resistência à compressão, resistência à tração e módulo de elasticidade e assim uma avaliação da influência do tipo de agregado e da reidratação na recuperação da resistência mecânica pôde ser feita.

Palavras-chave: concreto, altas temperaturas, propriedades mecânicas, reidratação.

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1. Introduction

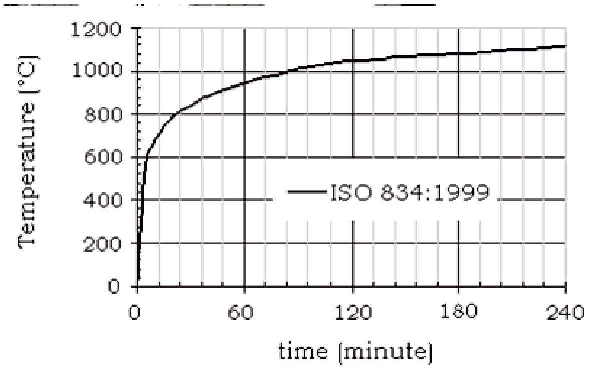
1.1 Exposure to fire

The capacity of a structure to preserve the integrity of its occupants during a given time under exposure to fire is denominated "fire endurance", ACI 216R-89 [2].
The standardized thermal method recommended by Associação Brasileira de Normas Técnicas in standard NBR 14432 [3] is that of the International Organization for Standardization: Fire-resistance Tests – Elements of Building Construction - ISO 834 [1]. Figure [1]1 shows the adopted ISO-834 standard (Standard Fire), which can be considered as basic and universally accepted as a standard temperature x time method.
Currently, there are few data showing how concrete behaves under high temperatures, mainly as a result from difficulties to perform tests in actual life scale.

1.2 Influence of the type of aggregate on the mechanical strength of concrete submitted to high temperatures

Considering that aggregates comprise about 70% of concrete, it is natural the type of aggregate to have a great influence on thermal properties and mechanical strength of concrete submitted to high temperatures.
The nature of minerals in aggregates is preponderant to the value of the thermal conductivity of hardened concrete: basalt has a low conductivity; limestone has a medium conductivity and quartz has the highest. Thermal conductivity is the thermal property that measures the capacity of a material to conduct heat. Similar to conductivity, the thermal diffusivity of concrete is also directly influenced by the type of aggregate: basalt, limestone and quartz. Diffusivity measures the speed of temperature change inside the material, Neville [4].
If the aggregate contains pyrite (iron sulfide - FeS_2), slow oxidizing around 150°C causes aggregate disintegration and, as a consequence, the rupture of concrete, NEVILLE [4]. Silicon aggregates, with a great amount of quartz (SiO_2), such as granite, arenite and a few shales, yield a sudden volume expansion when heated to approximately 500°C, Landi [5], Lin et *al*.[6]. At 573°C, quartz–α crystals transform themselves into quartz–β followed of an expansion of the order of 0,85%, Mehta & Monteiro [7],
Limestone (calcitic and dolomitic) aggregates are stable up to approximately 850ºC, when the decomposition of carbonate begins, forming calcium and magnesium oxides. Limestone aggregates are subject to expansions similar to those of the silicon aggregates starting only at 700ºC, due to decarburizing reactions and, similarly, they have the advantage of presenting a smaller difference in thermal dilation coefficient between the matrix and the aggregate, thus minimizing the destructive effects of differential thermal dilation, Mehta & Monteiro [7].
Calcination of limestone aggregate is endothermic: heat is absorbed, delaying the temperature rise. The calcinated material has a greater specific mass, providing surface insulation, a favorable aspect to robust elements, Neville[4]. However, calcination also causes aggregate expansion and fragmentation, cracking and carbon dioxide release, Lin at *al*. [6].
Souza & Moreno [8] studied the effect of high temperature on concrete prepared with granitic aggregate submitted to a maximum temperature of 600ºC. Compression strength was reduced to 86% in relation to the standard unheated value and tensile strength was reduced to 60%. Later, Moreno & Bizzo [9], repeated this same study, changing the heating rate; they obtained, in this case, a greater reduction. The influence of the heating rate was evidenced.

Figure 1 – Standard Temperature x Time fire Curve, ISO-834 (1)



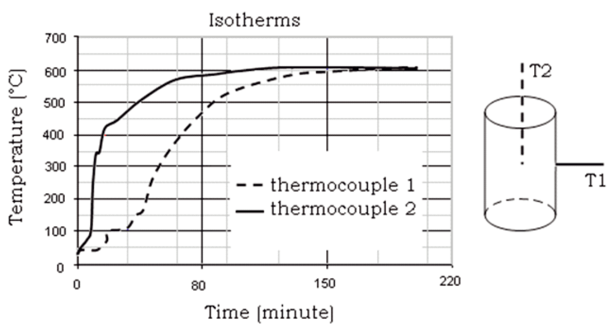
1.3 Recovery of the concrete mechanical strength after rehydration

According to Caraslindas & Barros [10], the exposure of concrete to high temperatures causes a decay of mechanical properties due to chemical and mechanical changes. These authors state that: "... heating concrete to temperatures close to 600ºC removes the hydrating water from the cement slurry. Further, the decrease in modulus of elasticity and strength is not recoverable after concrete is cooled to room temperature".
Contrary to the above mentioned authors, Cánovas [11] states that: "If the temperature of concrete is not higher than 500ºC, a later rehydration process can recover up to 90% of its initial strength after one year".
This recovery could be evidenced in a later occasion by Souza & Moreno [8], when concrete heated to a maximum temperature of 600ºC showed a recovery in compression strength around 80% and a recovery in tension strength around 98%.
Studies on the recovery of mechanical strength of concrete submitted to high temperatures and rehydration are not more than a few and contradicting. This fact justifies, then, the study of this variable in this work.

2. Experimental procedure

There are several variables that influence the behavior of concrete under fire, and one can point out the type of aggregate, maximum exposure temperature, concrete humidity, water/cement ratio, type of cement, size of test body, rate of temperature increase and cooling rate, workability of concrete and the type of cure.
In this work, the variables involved were the type of coarse aggregate, maximum exposure temperature (300º and 600ºC), re-

Figure 2 – (a) Evolution pattern of maximum exposure temperatures with time; (b) Points with instruments (on the surface – T1; and inside the concrete test body – T2)



hydration conditions for the recovery of mechanical strength after heating and the exposure time to temperature.

Constants were adopted as cement and fine aggregate, water/cement ratio, test body geometry, type of cure, humidity content, heating rate (standard curve ISO-834) and cooling rate (approximately 1ºC/minute). Test bodies made with the three concrete mixes were molded, with dimensions of 10 cm in diameter and 20 cm height, according to specifications in NBR 12821 – Preparação de concreto em laboratório (Preparation of concrete in the laboratory) and NBR 5738 – Moldagem e cura de corpos-de-prova cilíndricos ou prismáticos de concreto (Molding and curing cylindrical or prismatic concrete test bodies)

For each concrete mix (the first one with expanded clay aggregate, the second with basaltic aggregate and the third with limestone aggregate), 132 test bodies were molded; the proportions between materials, in mass, were equal to 1:2.93:1.37:0.57; 1:2.80:2.39:0.57 and 1:2.67:2.32:0.57; respectively, for cement, fine aggregate, coarse aggregate and water/cement ratio. All three mixes were prepared in a way to assure good workability – measured by the slump test and equal to 125 mm.

Test bodies were evaluated in regard to their compression strength, tension strength and modulus of elasticity after 100 days they had been molded (all test bodies remained in a humid chamber in this period), where, the increment of mechanical properties of concrete as a function of age was practically stabilized. Results obtained were taken as a comparison reference for samples heated to the maximum exposure temperatures (300ºC and 600ºC).

An oven specially developed for this study was used to evaluate the exposure time of each sample to maximum temperatures, Figure [2]. It is to be pointed out that this oven is capable of electronically simulating the heating rate of the standard curve ISO-834 [1]. This equipment has a central support for the test body and arrangements for thermocouples, which were embedded into samples, in orifices previously prepared during concrete pouring. All thermocouples were connected to an automatic data acquisition equipment. The distribution of thermocouples facilitated monitoring temperature inside the sample, being possible to monitor the evolution of temperature with time at points with instruments, according to the curve shown in Figure [2a]. This is a standard reference curve for test bodies made from the three concrete mixes and heated to the maximum temperatures of 300°C and 600°C.

The exposure time at the maximum temperature was that corresponding to the time required for thermocouple 1, located inside the test body made from each mixture, to reach the stipulated external temperature (thermocouple 2); in other words, it is the point where both curves meet, as illustrated in Figure [2b].

Table [1] shows the times relating to each mix and temperature under analysis. Having the times required for the stabilization of temperature inside the sample, test bodies were placed in another oven with a capacity of 6 samples, which also electronically controls temperature according to standard curve ISO-834.

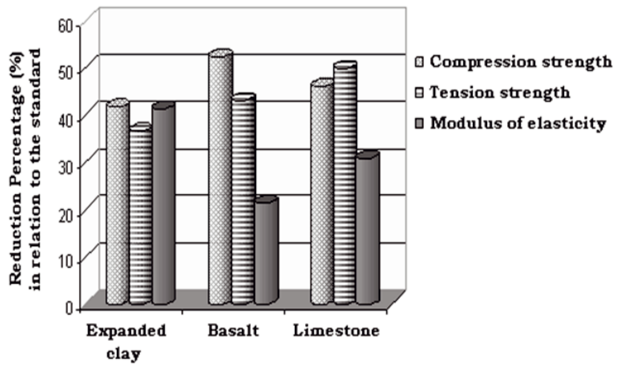
All samples remained in an oven for the period of 24 hours preceding heating tests (approximately at 100ºC) in order to assure a same humidity content. Once the heating process was finished, after the stipulated exposure time and maximum temperature, samples were gradually cooled to room temperature (approximately 25°C) inside the oven itself, at the rate of 1ºC/minute.

Once cooled, a few test bodies were tested in order to assess their mechanical strength (compression strength, tension strength and modulus of elasticity) and, therefore, to com-

Table 1 – Exposure at maximum temperature for each concrete mix under assessment

Temperature (°C)	Type of Aggregate	Time required for *thermocuple 2* to reach the external temperature (*thermocuple* 1)
300	Expanded clay	140 minutes
	Basalt	160 minutes
	Limestone	130 minutes
600	Expanded Clay	160 minutes
	Basalt	200 minutes
	Limestone	160 minutes

Figure 3 – Reduction in mechanical properties of the three concrete mixes after exposure to the maximum temperature of 600°C and cooling



pare the decrease in strength of heated concrete as a function of the type of aggregate and of the maximum exposure temperature.

Followed procedures to assess the strength recovery as a function of rehydration for each concrete test body made with one of the three types of aggregates proposed. In order to observe this influence, heated test bodies were separated in three groups; one was left in air, another was immersed in water and the third one was wrapped up in plastic film during 28, 56 and 112 days. Upon the end of each rehydration period, as above, specimens were tested for assessing their mechanical strength (compression strength, tension strength and modulus of elasticity) and, therefore, to obtain the evolution of the increase in mechanical strength as a function of time (28, 56 and 112 days) and of the rehydration process (immersed in water, wrapped up in plastic film and hydrated in environment air).

3. Results and Analyses

Results shown in charts that follow refer to recovery percentages of mechanical properties of test bodies submitted to the maximum exposure temperatures (300ºC and 600ºC) and different rehydration conditions, all compared to the standard (without heating) (Figure [3]).

Results shown evidence the decrease in mechanical properties for the three concrete mixes. The reduction in compression strength reach levels between 50% and 60%. For tension strength, the reduction was between 50% and 65% and for the modulus of elasticity the reduction reached levels between 60% and 80% in comparison to the initial values.

Charts shown in Figures [4], [5], [6], [7], [8] e [9] show recovery values for compression strength, tension strength and modulus of elasticity for the three concrete mixes heated to the maximum temperatures of 300ºC and 600ºC and obtained after the three rehydration methods for ages of 28, 56 and 112 days.

By observing the previous figures, where the recovery of mechanical strength of concrete prepared with different aggregates is assessed as a function of rehydration, one can verify the restricted influence of the type of aggregate in such recovery.

The recovery levels depend, mainly, from the rehydration method. For instance, after rehydrating concrete mixes by immersion in water during 112 days, the recovery was around 70% for compression strength, 80% for tension strength and 60% for the modulus of elasticity.

Figure 4 – Recovery in compression strength of the three concrete mixes related to the rehydration methods and process ages (Maximum Heating Temperature 300°C)

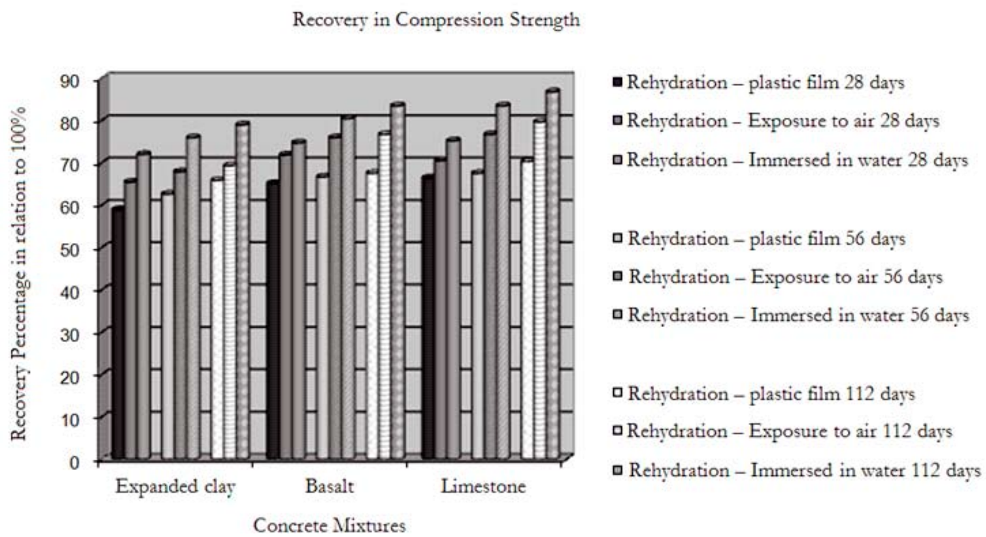


Figure 5 – Recovery in compression strength of the three concrete mixes related to the rehydration methods and process ages (Maximum Heating Temperature 600°C)

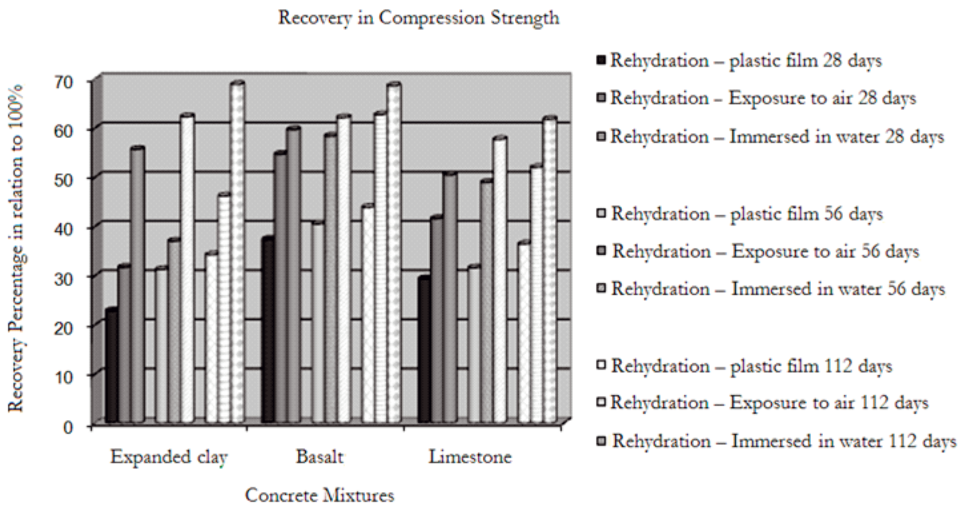
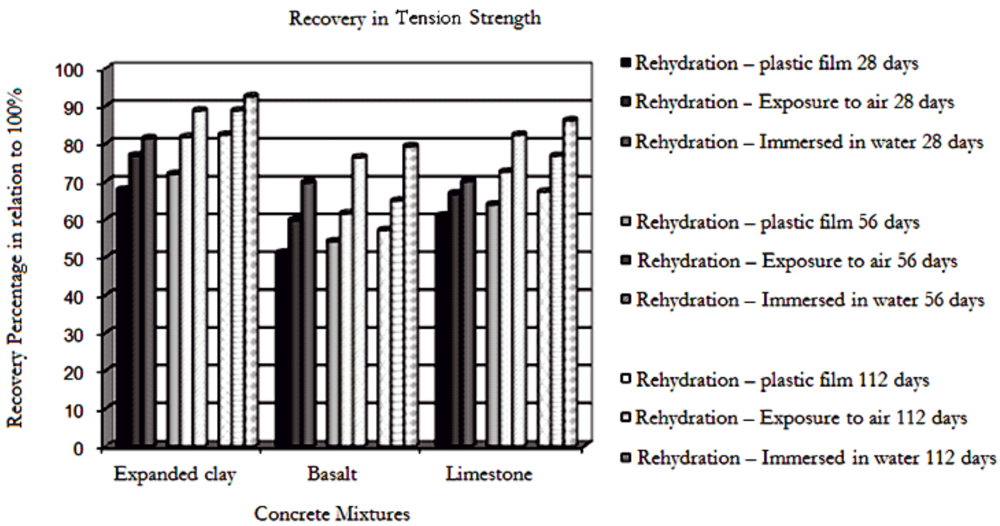


Figure 6 – Recovery in tension strength of the three concrete mixes related to the rehydration methods and process ages (Maximum Heating Temperature 300°C)



As already noted by CÁNOVAS [11], the concrete mechanical strength can be recovered up to 90% of the initial value with rehydration.

One can note from this work that this phenomenon does occurs, since tests made by other researchers show that the calcinated slurry, after rehydration, again shows losses of mass, mainly in the ranges of 150ºC - 400ºC and of 400ºC to 500ºC, respectively related to hydrated aluminates and portlandite. This fact leads to the belief that it might be a rehydration of compounds that had lost their structural water during calcination.

3.1 *Influence of the type of aggregate on the mechanical strength of concrete submitted to a temperature of 300ºC and 600ºC*

In relation to compression strength, results shown in previous figures evidenced a reduction between 20% and 30%, for the three mixtures prepared with the various types of aggregates, when heated to the temperature of 300ºC and slowly cooled.

In the case of tension strength, mixtures that used expanded clay and limestone as aggregate had a performance similar to that of

compression strength when exposed to 300°C, losing approximately 20% of its initial value. For concrete with basalt as aggregate this reduction was 40%.
The modulus of elasticity was the mechanical property that showed the most significant reduction when test bodies were submitted to 300ºC. This reduction was around 35% for the mixture that used expanded clay as aggregate and 43% and 50% for mixtures that used basalt and limestone as aggregate, respectively.
For the exposure temperature of 600ºC, a great reduction in compression strength for the mixture that used expanded clay as aggregate was observed, approximately 60%. Mixtures that used basalt and limestone as aggregate had a reduction of 48% and 55%, respectively. In relation to tensile strength, mixtures that had the greatest reductions were those that had expanded clay and basalt as aggregates, around 65% and 57%. For mixtures that used limestone, the reduction was approximately 50%.
The mixture that had the best behavior in relation to the modulus of elasticity, when heated to 600ºC, was the one which used ex-

Figure 7 – Recovery in tension strength of the three concrete mixes related to the rehydration methods and process ages (Maximum Heating Temperature 600°C)

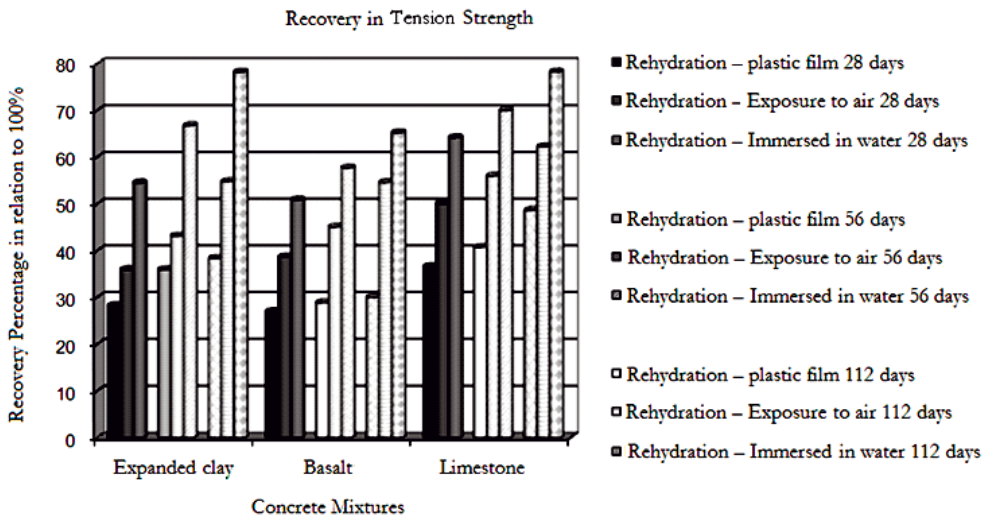
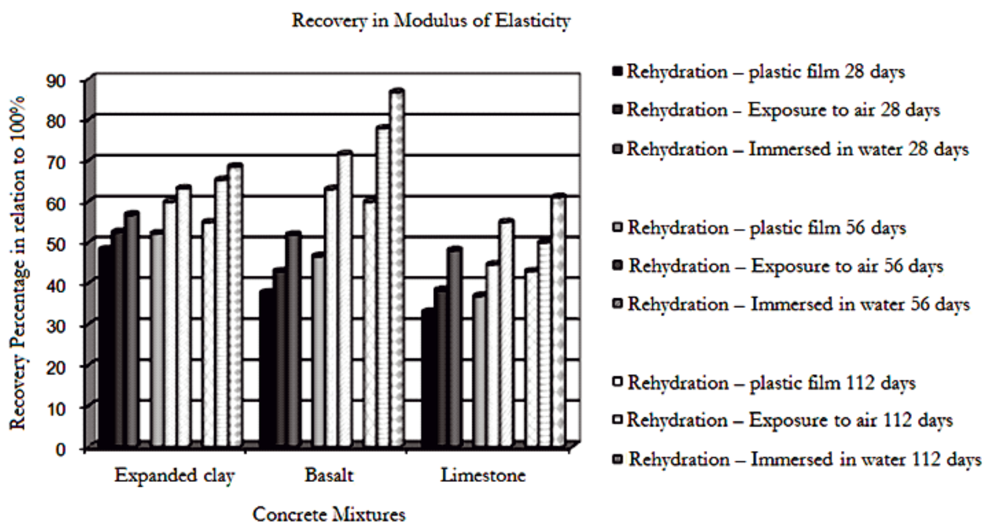


Figure 8 – Recovery in modulus of elasticity of the three concrete mixes related to the rehydration methods and process ages (Maximum Heating Temperature 300°C)

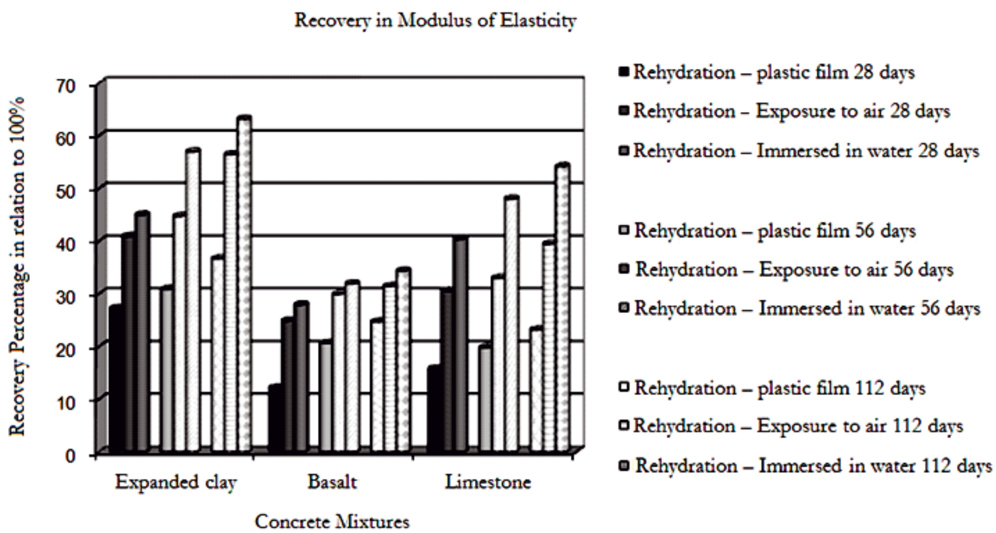


panded clay, with a reduction of 60% in comparison to the initial value. The mixtures with basalt and limestone had reductions of 80% and 70%, respectively.
In the case of the three mixtures analyzed, that with the best performance in relation to compression strength and tensile strength after being heated to 300ºC and slowly cooled was the one which used basalt as aggregate. Expanded clay as aggregate provided the best result for the modulus of elasticity.
For the temperature of 600ºC, mixtures produced variations that made it impossible to determine which one had the best behavior for at least two properties. The best behavior for compression strength was observed in the mixture that used basalt as aggregate. In relation to tensile strength, concrete prepared with limestone as aggregate had the smallest loss, around 50%. For the modulus of elasticity, the best behavior was that of concrete prepared with expanded clay as aggregate, a loss of around 40%.
The decrease in compression strength for heated concretes depends on factors such as the heating rate, cooling rate and, mainly, the type of aggregate.
Results of this work have shown that the degree of change in mechanical properties of concrete exposed to high temperatures is strongly influenced by the type of aggregate. However, it is noted that one can not exclude from these parameters the heating rate, the exposure time at maximum temperature, cooling rate, humidity content and, as noted by Caraslindas & Barros [10] the density of concrete. These parameters, certainly, must be analyzed in future research work on this subject.

3.2 Rehydration processes

The various rehydration conditions adopted in this work were responsible for a greater or smaller recovery in mechanical strength of concrete after heating.
Test bodies prepared with basalt and limestone as aggregate, when exposed to a maximum temperature of 300ºC and rehydrated during 112 days, immersed in water, had a recovery in compression strength around 90% and, similarly, the mixture made with expanded clay had a recovery of 80%.
When exposed to the maximum temperature of 300ºC, test bodies that were rehydrated in environment air yielded intermediate recovery values for compression, when compared to samples that remained immersed in water and with those that were wrapped up in plastic film (without exposure to the environment). It is pointed out that test bodies wrapped up in plastic film yielded values smaller than those for the other two rehydration processes, however significant, between 65% and 70%.
In relation to tensile strength, all three concrete mixtures had a significant loss when exposed to 300ºC. After 112 days rehydrating in water, recovery was around 95% for the mixture prepared with expanded clay as aggregate, around 80% for the mixture made with basalt as aggregate and 85% for the mixture made with limestone. In this case, it is convenient to note that recovery, for a same age, considering the rehydration process in environment air, reached indexes close of those obtained for test bodies immersed in water (with a difference 10% less).
For the modulus of elasticity, test bodies exposed to 300ºC had a more significant reduction of their values. When submitted to rehydration by immersion in water, the recovery for mixtures made with expanded clay and basalt as aggregates was 65% and 86%, respectively, for the age of 112 days. For the mixture that used limestone as aggregate the recovery was 60%.
It is important to note that the results of this work evidence without any doubt the recovery of most of mechanical strength of heated concretes after rehydration. Confirming Cánovas [11], if the temperature of concrete is not higher than 500ºC, a rehydration process later can recover up to 90% of its initial strength after one year. This recovery could be evidenced, also, in studies performed by Souza & Moreno [8], where concrete test bodies

Figure 9 – Recovery in modulus of elasticity of the three concrete mixes related to the rehydration methods and process ages (Maximum Heating Temperature 600°C)



(measuring 10 cm x 20 cm) heated at maximum exposure temperatures of 300°C, 600°C and 900°C, and immersed in water during 112 days, had a recovery in compression strength of 93%, 85% 45%, respectively.

4. Conclusions

The research described in this paper provided data on how mechanical properties of concrete prepared with different aggregates can be influenced by high temperatures. Particularly, it shows results for concrete prepared with basalt as aggregate, the behavior of which is not mentioned in national and international standards or building codes of common utilization in Brazil.

Results obtained from this research evidenced a strong decrease in compression strength for the maximum exposure temperature of 600ºC. This result, in a greater or smaller percentage, was already expected, having as a basis previous studies on the subject.

Similarly, it was observed that concrete rehydration, after heating, can contribute for recovering a significant portion of the initial mechanical strength, either in relation to compression, tension or modulus of elasticity. It was also noted that test bodies kept in water recovered a major portion of their initial strength with time. The recovery levels mainly depend on the type of rehydration method, and the type of aggregate has a minor influence.

The fact that the reference values recommended by NBR 15200 [12] are against safety should be carefully assessed. Although not clear in the text, the values recommended refer to a concrete that was heated under load and hot tested. It is then here suggested to incorporate into the National Standard Code an indication of decreases in strength for concretes heated without being submitted to loads and tested after slowly cooled, as in the case of international standards and building codes.

In finishing, it is noted that results obtained were coherent, if compared to previous studies on this same subject. However, it should also be noted once more that there are many variables involved in the problem and any change in these variables can result in significant differences between results from researches on the subject. As variables, one can point out humidity content, water/cement ratio, type of aggregate, the exposure time to temperature, heating rate and cooling rate. Therefore, a broad generalization of results obtained by different researchers is rather difficult. The above mentioned factors should be taken into account upon interpreting results.

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