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Durability performance of concrete bridge piers made with metakaolin and latex mixes

A. Camões, P.J.S. Cruz, S. Jalali, R.M. Ferreira
Department of Civil Engineering, University of Minho, Guimarães, Portugal

P. Cunha
ICORR, Portugal

ABSTRACT: Requirements for assessment of structural performance based on a combination of concrete strength and reinforcement cover seems to be insufficient to provide adequate durability of reinforced and prestressed concrete structures. Under these circumstances, the construction industry is expected to generalize the use of higher quality concrete with an enhanced or even high performance.

This paper summarizes the main results of several tests to assess the durability performance of different concretes used in the construction of a new highway bridge in the north of Portugal. In this report, only the metakaolin and latex results are discussed. The durability performance was evaluated with tests based on capillary absorption, permeability to oxygen and water as well as chloride diffusivity and electrical resistivity. The results demonstrated that the use of metakaolin and latex improve the resistance against chloride penetration, while the effect on water and oxygen permeability is not so clear.

1 INTRODUCTION

The use of conventional concrete, even in common constructions has revealed to be technically and economically inadequate. The reinforced and prestressed concrete structures deteriorate rapidly causing high evaluation, maintenance, retrofitting and rehabilitation costs. Associated with this is the decrease of the service life of the structures. Therefore, the study of the life cycle of structures is nowadays an increasingly important subject.

As part of the general design, the durability of concrete is typically being specified in the form of some prescriptive requirements to maximum w/c-ratio and minimum cement content and concrete cover. Even for relatively new concrete structures, where the prescriptive durability requirements have been in accordance with the new European Concrete Code EN 206-1, premature degradation of concrete is being observed.

No references exist in standards to the use of metakaolin additions or latex additives in concrete mix designs. In order to obtain a better understanding of the long-term performance of concrete structures using these materials, much research work has been carried out in recent years (Boddy et al. 2001, Rossignolo & Agnesini 2004). The need for experience of concrete structures with these additions compared to that of pure portland cements is needed. The additions affect both the chemical and physical characteristics of the concrete in such a way that the resistance both against chloride penetration, carbonation, alkali-aggregate reaction and chemical deterioration is generally improved.

The Civil Engineering Department of the University of Minho had recently the opportunity to investigate the durability performance of the different concrete types used in the construction in a new highway bridge over the Ave River, in the north of Portugal. In different piers, use has been made of the addition of silica fume (10% of the cement weight was replaced), fly ash (20% of the cement weight was replaced), metakaolin (10% of the cement weight was replaced), latex and corrosion inhibitors, to allow comparative assessment of durability properties related to a reference concrete mix. In this report, only the metakaolin and latex results are discussed. An extensive number of specimens was prepared to control the concrete durability under laboratory and in situ conditions.

Figure 1. Bridge over the Ave River.

For the assessment of the concrete durability, several laboratory tests were performed on specimens moulded in situ during the cast of the structural elements. Capillary absorption, permeability to oxygen and water as well as chloride diffusivity and electrical resistivity were measured. As a reference test, the compressive strength was also measured.

Figure 2. East access viaduct of the bridge over the Ave River.

Figure 3. Images of the application corrosion sensors used and their installation.

Corrosion sensors were installed in some specimens and in some structural elements in order to monitor in situ the corrosion of the reinforced concrete at different depths of concrete cover.

With measurements of potential differences, tendencies for concrete degradation can be determined regarding the carbonation and chloride penetration.

This paper provides an overview of the main results obtained in the tests preformed in the laboratory and in situ.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

In the current experimental program, three different concrete mixes were used (Table 1), having been designed as C30/37 (according to EN 206-1 code), using CEM I 42.5 R cement. The concrete mixtures had a water/binder ratio of 0.44. For all concrete mixtures, a naphthalene-based superplasticizer with a solid content of 42% was used, while the aggregate was mostly of siliceous origin with a maximum particle size of 25 mm. Two different additions where used: high reactivity metakaolin (10% of cement weight was replaced) and a commercially available latex (5% of cement weight was added). A third concrete mix, made without additions, was used as a reference mixture.

Table 1. Mix proportions used.

Material	Metakaolin concrete	Latex concrete	Reference concrete
Cement (kg/m^3)	315	350	350
Fine Sand (kg/m^3)	365	365	365
Coarse Sand (kg/m^3)	411	411	411
Gravel 19 mm (kg/m^3)	495	495	495
Gravel 25 mm (kg/m^3)	522	522	522
Water (l/m^3)	155	139	155
Superplasticizer (l/m^3)	3.5	3.5	3.5
Additive quantity (kg/m^3)	35	17.5 (l/m^3)	---

For each concrete mixture an extensive number of specimens was produced on the construction site comprising: ∅100 x 200 mm concrete cylinders; ∅150 x 300 mm concrete cylinders and 150 mm and 250 mm concrete cubes. After casting, all specimens were kept under plastic sheets until demoulding the following day. Thereafter, the specimens were stored in water at 21 ± 2 ºC until time of testing. All laboratory tests were performed at approximately 400 days of age.

2.2 *Testing procedures*

The compressive strength test, performed according to the LNEC E-226 specification, was used as a reference test procedure. In order to test the resistance against chloride penetration, an accelerated non-steady state migration test method was applied (Nordtest Method NT Build 492). As part of this testing, the electrical resistivity of the concrete was also recorded. In addition, the ASTM C 1202 standard for electrical indication of concrete's ability to resist ion penetration was also performed. Furthermore, the electrical resistivity of the concretes was also measured which is an indicative of the concrete resistance to chloride ion penetration.

The capillary water absorption test followed the LNEC E-393 Specification.

The permeability to water and oxygen tests were performed based on LNEC E-392 specification, using the apparatus developed at Leeds University (Cabrera 1999). This device ensures that the specimen is subjected to a steady state flow of the fluid that passes through the sample under a given pressure for a given period of time. The cylindrical specimens with a diameter of 50 mm and 40 mm high were used.

The monitoring systems measured the electrochemical potential of the reinforcement steel and of two probes of the same material at two different depths (15 and 30 mm respectively).

The same system also measures the concrete's electrical resistivity between those two levels, as well as the current intensity of the free macrocell at those depths. The instant corrosion velocity can also be determined using these sensors and resorting, for example, to the Linear Polarisation Resistance (LPR) technique.

3 RESULTS AND DISCUSSION

Table 2 includes the main results obtained in the laboratory experimental program. Each value is the average of the results recorded from three specimens, followed by the corresponding coefficient of variation.

Table 2. Results obtained.

	Metakaolin concrete	Latex concrete	Reference concrete
Compressive strength, f_c (MPa)	56.1/2.6	54.2/5.3	57.3/2.9
Coulomb test, Q (C)	2274/5.9	3658/9.3	4978/5.8
Rapid migration test, D ($\times 10^{-12}$ m^2/s)	7.8/12.8	14.5/15.9	24.4/7.8
Electrical resistivity, ρ (Ωm)	601.4/0.9	453.2/1.6	377.8/2.9
Capillary absorption, K_c (kg/m^2/min$^{0.5}$)	0.058/3.2	0.049/7.9	0.059/4.4
Water permeability ($\times 10^{-18}$ m^2)	2.50/11.3	2.41/36.0	6.56/7.8
Oxygen permeability ($\times 10^{-17}$ m^2)	8.32/8.0	7.18/30.5	4.94/23.1

3.1 *Compressive strength*

From Table 2 it can be seen that the compressive strength is similar for all the mixtures tested and that the use of metakaolin and latex has not affected the strength gain of the concrete.

3.2 *Chloride migration and diffusivity*

As shown in Table 2, the coefficient of diffusion improves in performance from the reference concrete to the latex and metakaolin concrete. Based on previous experience (Table 3), the observed results indicate that the metakaolin concrete has a high resistance against chloride penetration. The latex and the reference concretes have a moderate and low resistance against chloride penetration, respectively (Table 5).

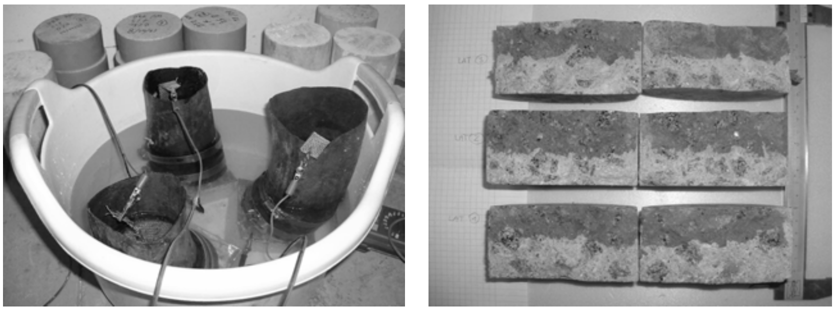

Figure 4. Rapide chloride migration test (NT Build 492).

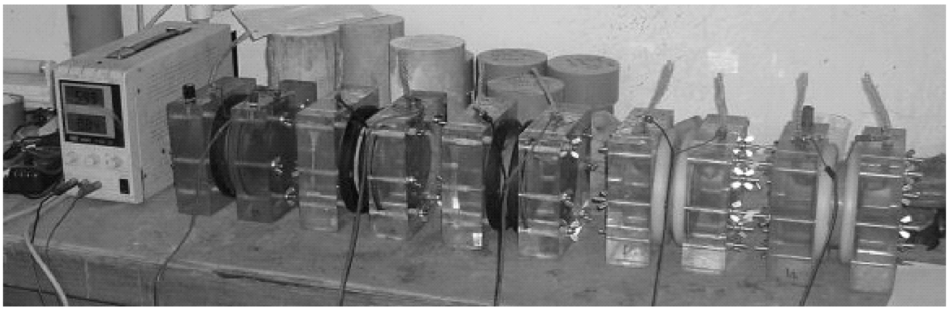

Figure 5. Tests apparatus for the evaluation of the concretes ability to resist chloride penetration (ASTM C1202).

Table 3. Resistance against chloride penetration based on non-steady state migration testing (Gjørv 1996).

Chloride Diffusion D ($\times 10^{-12}$ m^2/s)	Concrete Resistance
> 15	Low
10 – 15	Moderate
5 – 10	High
2.5 – 5	Very high
< 2.5	Extremely high

Both ASTM C1202 and the NT Build 492 tests (Figs 4 and 5) show the same pattern regarding the concretes performance against ion penetration. The classification of the ion penetration performance as a function of the charged passed through the specimen is given in Table 4. The metakaolin and latex are classified as sustaining a medium penetration to ions, where as the RC is subject to a high ion penetration. Based on the two tests, both the use of metakaolin and latex in the concrete mix seems to improve the concretes performance against chloride ion penetration.

Table 4. Classification of ion penetration according to the charged passed (Andrade & Whiting 1996).

Charge passed Q (C)	Chloride Penetration
> 4000	High
> 2000 and < 4000	Moderate
> 1000 and < 2000	Low
> 100 and <1000	Very low
< 100	Negligible

3.3 *Electrical resistivity*

For a given concrete with a given moisture condition, there is a close relationship between chloride diffusivity and electrical resistivity (Gjørv 2003). Therefore, both of these parameters should reflect the resistance of the concrete against chloride penetration. By applying such accelerated testing as that in the present work, however, it may be argued that the obtained test results do not properly reflect the complete resistance of the concrete against chloride penetration. Therefore, the results should reflect the difference of the various binders to resist chloride penetration into concrete. This is confirmed buy viewing the values in Table 2.

Figure 6. Capillary absorption test.

3.4 *Capillary absorption*

From the result presented in Table 2, although there are no significant reductions in the capillary absorptions coefficients presented, the latex concrete seems to have slightly lower values than the other two concrete types. However, the values show a rather low tendency to capillary absorption.

3.5 *Oxygen and water permeability*

For the water permeability, both metakaolin and latex improve the performance compared with the RC. For the oxygen permeability, it is the reference concrete that demonstrates better performance. The values, however, are in accordance to general experience (Grube & Lawrence 1984, Yssorche et al. 1995). The order of magnitude between the values of water and oxygen permeability observed for concrete tested with the Leeds permeator is also in accordance with general experience (Ferreira 2000).

Figure 7. Oxygen and water permeability test.

3.6 *Monitoring systems*

After the conclusion of the structure, electrical potential measurements at 159 points in the bridge were performed, 15 of which were in the active state.

Approximately 4 months later, 9 of these points confirmed the active state both of the probes and of the reinforcement steel. In these active zones (Z1, Z2, Z3) the electrical resistivity was also measured. The values are presented in Table 5.

Table 5. Potential values (to graphite electrode) and resistivity.

	V (mV)	Resistivity (kΩcm)
Z1		
steel	- 361	12.8
1st level	- 354	12.8
2nd level	- 110	12.8
Z2		
steel	- 341	9.4
1st level	- 600	9.4
2nd level	- 342	9.4
Z3		
steel	- 567	8.8
1st level	- 346	8.8
2nd level	- 359	8.8

At the same time, the corrosion velocity at the two different depths was measured resorting to the LPR technique, using 3 of the probes and a portable potentiostate.

The values of corrosion current density vary between 0.22 and 0.49 μA/cm^2 considered low corrosion velocities (Nuclear Energy Agency 2002). These values correspond to a loss of thickness in the reinforcement steel between 2.61 and 5.71 μm per year, as Table 6 show.

Table 6. Values of LPR technique (corrosion rate).

	Depth	
	15 mm	30 mm
Z3		
i_{corr} (μA/cm^2)	0.23	0.35
v_{corr} (μm/year)	2.72	4.08
Z4		
i_{corr} (μA/cm^2)	0.49	0.22
v_{corr} (μm/year)	5.71	2.61

It is, however, too soon to determine a tendency for the corrosion velocity and potentials of these points, since few measurements have been made.

It can be expected that over time, and with more readings, the tendencies become clearer.

As for the piers of different composition, it is still not possible to know which of the mixtures has the best anti-corrosion performance. All piers present a passive state and high values of concrete electrical resistivity.

To accelerate the corrosion process several specimens (250x250x250 mm3) were submerged cyclically in a solution with a NaCl concentration of 3% in weight of the ion chloride.

On the other hand the probes where these different mixtures are tested present different responses to chloride attack: some are more sensitive as metakaolin and latex while others are more resistant and have a lower corrosion velocity (Table 7). These values are confirmed by the LPR technique.

Table 7. Corrosion rates.

Concrete	Samples		Level of corrosion (Nuclear Energy Agency 2002)
	Level 1 (μA/cm^2)	Level 2 (μA/cm^2)	
Metakaolin concrete	1.016	0.769	High
Latex concrete	1.055	0.674	High
Reference concrete	0.532	0.662	Moderate
Inhibitor	0.926	0.809	Moderate
Silica fume	0.446	0.418	Low

4 CONCLUSIONS

The present experimental investigation was based on a restricted number of variables and the evaluation of the parameters was based on a limited number of test specimens and in situ measurements. However, based on the test results obtained, the following conclusions appear to be warranted.

Of the various concretes tested, the obtained laboratory results demonstrate the beneficial effect of metakaolin and latex addition to improve the concrete durability, namely the resistance against chloride penetration, which is in general agreement with existing experience (Boddy et al. 2001, Rossignolo & Agnesini 2004).

Test results demonstrate that the use of metakaolin and latex addition does not seem to affect long term strength gain when compared to ordinary portland cement.

Whilst the monitoring systems readings may not seem of high importance yet, they will allow for a careful monitoring of bridges, planning its maintenance and avoiding the high costs of a late repair.

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