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The effect of metakaolin on chloride penetration into concrete

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ABSTRACT

Extensive research and practical experience have shown that partial replacement of cement by metakaolin improves concrete durability as a result of the refinement of the pore structure. While literature confirms much research on the performance of concrete with metakaolin, it is scarce concerning the performance with regards to chloride penetration.

For the study, reference mixes where made with CEM I 42,5R cement. Two contents levels where defined: 330 kg/m^3 and 440 kg/m^3 based on mix designs currently used in the ready-mix industry for C20/25 and C30/37 concretes. Cement was partially replaced with metakaolin with levels varying from 10-20%. All mixes where tested for compressive strength, electrical resistivity and chloride diffusion characteristics (migration and immersion testing).

The results demonstrate the improved resistance to chloride penetration of concretes with metakaolin additions. In addition, a beneficial effect on strength and durability properties of metakaolin also observed. Service life design calculations of reinforced concrete structures in marine environment based on the result obtained show a significant increase in the time to fulfill the serviceability limit state of corrosion initiation.

Key words: Durability, metakaolin, chloride penetration, electrical resistivity, service life

1. INTRODUCTION

Metakaolin (MK) is produced from calcining kaolin clay at a specific temperature range (600-800 °C) to make it reactive, with the general form Al_2O_3-SiO_2. Literature confirms that partial replacement of cement by MK improves concrete strength and durability as a result of the refinement of the pore structure. Besides the performance benefits of using MK in concrete, there are also ecological benefits, which make MK concrete a more sustainable alternative to OPC concrete. The production of MK does not release CO_2 as does that of OPC as a result of the decarbonation of limestone, and, lower temperatures are required to produce MK, hence lower energy required. While much research on the mechanical and durability performance of concrete with MK has been performed, it is scarce with regards to chloride penetration. Kim [1] shows the identical, performance of MK with silica fume (SF) measuring the total charge passed (ASTM C 1202). Studies by Boddy [2] show that circa 8% MK in concrete can reduce diffusion coefficents by 50%, where as 12% MK can reduce apparent diffusion coefficient (D_A) by 30%. Zeljkovic [3] also studied the total charge passed and D_A with similar results. Nokken [4] work shows similar tendencies, with 8% MK having identical performance as that of 4% SF.

2. MATERIALS, CONCRETE MIXTURES AND TEST PROCEDURES

In this study, the pozzolanic effect of MK additions in OPC concrete was studied. Two cement contents levels where chosen based on mix designs currently used in the ready-mix industry for C20/25 and C30/37 concretes: 330 kg/m^3 and 440 kg/m^3, respectively. Cement was replaced with MK with levels varying from 10-20%. All concretes where tested for compressive strength, electrical resistivity, non-steady state chloride migration and chloride immersion.

A CEM I 42,5R (Secil) cement was used in the production of concrete specimens, in accordance to the NP EN 197-1. A commercially available metakaolin (Optipozz) used was - Class N according to the ASTM C 618. In Table 1 the chemical and physical characteristics of the cements and metakaolin used are presented.

Table 1 – Properties of cements and metakaolin

Parameters (%)	SiO_2	Al_2O_3	K_2O	Na_2O	Fe_2O_3	CaO	SO_3	MgO	Cl^-	Sg*	Ss*
CEM I 42,5R	19.55	4.24	-	-	3.34	62.61	3.26	2.51	0.03	3.12	4071
Metakaolin	51.50	44.51	0.21	0.11	0.45	0.02	-	0.12	-	2.20	

* Sg – specific gravity; Ss – specific surface (cm^2/g)

Two course aggregates and a river sand were used. The course aggregates with size 5-15 mm and 15-30 mm have specific gravity of 2.65 g/cm^3 water absorption of 1.50 %. The river sand had specific gravities of 2.63 g/cm^3 and absorption of 1.04 %. Mix design was based on maintaing a constant water/binder (w/b) ratio. A 0.45 w/b ratio for mixes with 440 kg/m^3 of binder, and a 0.60 w/b ratio for mixes with 330 kg/m^3 of binder. Each serie was comprised of a references mixture with no MK, and mixes with 10%, 15% and 20% of cement replacement with MK. Details of the concrete mixtures are presented in Table 2. Concrete workability was kept within the S2 class of the NP EN 206-1.

Table 2 – Concrete compositions for references mitures

Series	w/b	Water (l/m^3)	Binder (kg/m^3)		Aggregate (kg/m^3)			Slump (mm)
			Cement	MK	Course 1	Course 2	Sand	
330-0 (REF)	0.60	198	300	0	405	835	710	80
440-0 (REF)	0.45	200	440	0	420	820	600	90

All concrete mixes where produce in a vertical axis mixer with a 120 litre capacity. Cubic specimens of 100 mm and 150 mm in dimension and cylinders of 100 mm in diameter and 200 mm in height where cast in steel moulds and compacted using a vibrating table. 24 hours after casting the specimens where removed from the moulds and permanently cured in water tanks at 20 ± 3 °C until testing. Testing was performed at 7, 14, 28, 90 and 180 days.

The compressive strength of the concrete was evaluated on 150 mm cubes according to the NP EN 12390-3. The electrical resistivity (ER) of the concrete was determined using a four-probe resistivity-meter (RM MK II - alternating trapezoidal current wave - 13 Hz) on 150 mm cubic concrete specimens, according to LMC testing procedure for ER of concrete [5]. The non-steady state chloride migration coefficient was determined on cylindrical specimens of 100 mm diameter and 50 mm height according to the LNEC E463 [6]. The chloride immersion test was performed on 100 mm cubic specimens according to the LNEC E390 [7].

3. RESULTS AND DISCUSSION

An analysis of the result in Table 3 reveals the well-known beneficial effect of metakaolin on compressive strength, *i.e.*, refinement of the pore structure due to pozzolanic reaction. All levels of replacement showed improvement (already at 28 days). Significat inprovement is observed for 15% replacement for the 440 kg/m^3 mixes (± 20%).

Table 3 – Compressive strength and electrical resisitivty results

Series	Average compressive strength (MPa)					Average electrical resisitivty (Ωm)			
	7 days	14 days	28 days	90 days	180 days	7 days	28 days	90 days	180 days
330-0 (REF)	18.87	22.17	23.87	28.07	29.07	30.03	39.53	49.48	50.80
330-10	17.00	22.20	26.60	31.10	31.83	25.58	73.13	74.05	74.89
330-15	14.93	20.97	25.03	31.53	33.10	21.67	65.36	65.68	66.37
330-20	12.37	18.77	23.40	29.63	33.60	20.30	62.46	63.18	65.93
440-0 (REF)	30.53	33.73	40.62	44.03	44.77	38.27	54.84	71.58	72.53
440-10	30.23	35.87	40.90	44.80	45.40	32.58	95.51	95.93	96.68
440-15	32.67	40.43	47.97	53.67	54.57	39.34	124.75	127.10	127.98
440-20	24.73	32.07	39.73	46.77	47.63	30.16	85.99	107.61	112.53

The electrical resisitivty (ER) results in Table 4 show an improvement in the performance of concrete with MK additions at early ages. At 28 days, 25-75% increase in ER is observed in concrete with MK. From this date onward no significant increase is observed except for aslight increase in the values of the reference concrete.

Table 4 – Results of the non-steady state migration and immersion test

Series	Migration coefficient (e^{-12} m^2/s)				D_A (e^{-12} m^2/s) / c_S (%/mass binder) *		
	7 days	28 days	90 days	180 days	D_A	c_S	Depth (mm) of 0.08% cl
330-0 (REF)	53.99	31.28	30.66	29.41	12.00	5.24	> 40
330-10	47.77	15.84	13.43	13.38	3.52	7.98	[15-20]
330-15	59.13	17.05	14.31	14.22	3.95	8.73	[20-25]
330-20	51.06	23.10	15.15	14.86	2.78	6.99	[20-25]
440-0 (REF)	25.11	15.49	13.18	13.15	4.82	5.34	[20-25]
440-10	26.69	8.52	8.32	8.14	3.62	4.65	[15-20]
440-15	24.15	7.03	6.64	5.77	2.32	6.59	[10-15]
440-20	27.35	10.49	7.34	6.26	1.35	11.86	[10-15]

* D_A – Average apparent diffusion cofficiente; c_S – Average surface chloride concentration

From table 4 it can be observed that the chloride migration coefficient at 28 days, for mixes with MK, is already 50% lower than the references mixes. At 180 days the tendency maintains. The apparent diffusion coefficient calculated by curve fitting of the chloride profiles is roughly 75% lower for the 330 kg/m^3 binder mixes, and between 20-70% lower for the 440 kg/m^3 binder mixes. For all concretes with MK, the depth of the critical chloride concentration is always lower than that of the reference mixes.

The average chloride profiles measured from the specimens subject to the immersion test are presented in Figures 1 and 2. The results of the curve fitting of Fick's 2nd Law of diffusion to the chloride profiles (D_A and c_S) are presented in Table 4.

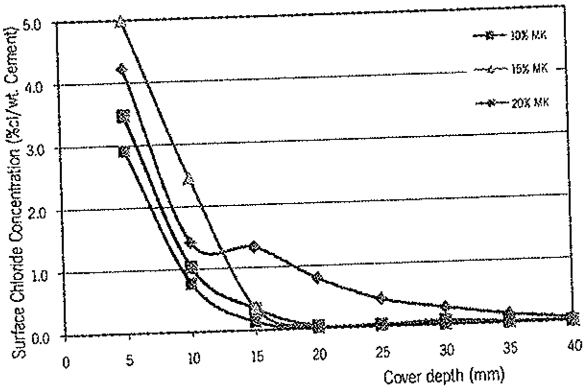

Figure 1 – Chlordie profiles for 330 kg/m³ binder mixes

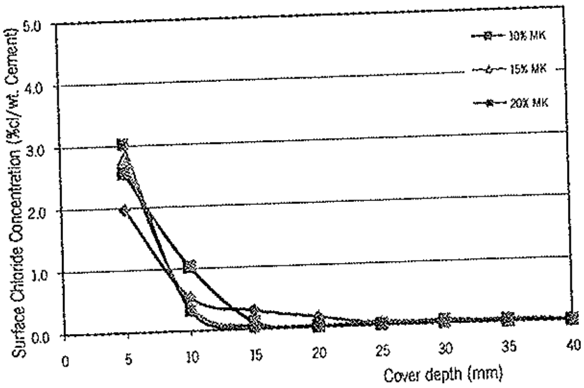

Figure 2 – Chlordie profiles for 440 kg/m³ binder mixes

4. CONCLUSIONS

The present study was only based on a limited number of test methods, which may not reflect the complete performance of concrete against chloride penetration. However, based on the results obtained, MK additions improve the performance OPC concrete (when < 20%) with regards to chloride penetration. Concretes with MK have lower apparent diffusion coefficients from immersion testing, lower diffusion migration coefficients and higher electrical resistivity, especially from 28 days onwards, independent of the % of MK substituition. Concrete will have a longer service life in marine environment due to the beneficial effect of MK.

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