Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 3(5):228-233

Use of Low-CO_2 Portland Limestone Cement for Pavement Construction in Canada

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Abstract: In response to growing pressures to reduce the clinker content in cement and hence the CO_2 emissions associated with its production, the Canadian Standards Association (CSA A3001-08) introduced a new classification of cement in 2008, this being Portland limestone cement (PLC) containing up to 15% limestone. PLC is now permitted in the production of all classes of concrete in Canada except for sulfate-exposure classes (CSA A23.1-09). Considerable laboratory testing has been conducted in Canada in recent years to demonstrate that PLC with up to 15% limestone can be manufactured to produce equivalent performance to a Portland cement in terms of concrete strength and other properties, including durability. The equivalent performance is achieved by optimizing the PLC with regards to composition and particle-size distribution, and this is achieved by intergrinding rather than blending of the Portland cement and limestone. This paper presents data from a number of recent full-scale field trials where PLC has been used in paving projects in Quebec, Alberta, and Nova Scotia. In each field trial, the performance of PLC concrete has been compared with that of equivalent concrete produced using Portland cement (PC), and concretes have been produced with varying levels (up to 50%) of supplementary cementing materials (SCM). Testing of concrete produced during the field trials has included compressive strength, freeze-thaw and deicer-salt-scaling resistance, chloride permeability, and chloride diffusion. The results indicate that concrete performance is strongly influenced by the level of SCM used, but is independent of whether PLC or PC is used. The use of such PLC has the potential to bring about a 10% reduction in the greenhouse gas emissions associated with the production of Portland cement clinker. The acceptable performance of concrete containing combinations of PLC and SCM will permit further reductions in the CO_2 footprint of the concrete; in one mix, the clinker content was just 41% of the total mass of cementing material.

***Key words**: Cement reduced clinker; Concrete paving; Fly ash; Portland limestone.*

Introduction

Portland limestone cement (PLC) is produced by blending Portland cement and limestone or, preferably, intergrinding Portland cement clinker, limestone, and calcium sulfate. Such cements have been allowed by the European Standard, EN197-1, since 2000, although a number of European countries allowed their use through national standards for a decade or more prior to this date. EN197-1 allows up to 20% limestone in CEM II/A cements and up to 35% in CEM II/B cements. In Canada, Portland limestone cement containing up to 15% limestone was first permitted by the cement standard (CSA A3001) in 2008 and by the concrete standard (CSA A23.1) in 2009. Prior to acceptance of PLC in the Canadian Standards, considerable laboratory testing was performed to demonstrate that PLC containing up to 15% limestone could be manufactured to provide equivalent performance to Portland cement (PC) in terms of strength and durability in concrete mixes with and without supplementary cementing materials (SCM). Some of the laboratory data have been recently published [1, 2]. The equivalent performance is achieved by optimizing the PLC with regards to composition and particle-size distribution, and this is achieved by intergrinding rather than blending of the Portland cement and limestone. It should be noted that up to 5% interground limestone is permitted in ordinary PC in Canada and that typically PC will contain approximately 3 to 4% limestone interground with the cement and clinker. The acceptance of PLC as a substitute for PC potentially allows the clinker content of cements in Canada to be reduced by up to about 10%. The production of Portland cement clinker results in significant CO_2 associated with the calcination or decarbonation of limestone ($CaCO_3 \xrightarrow{heat} CaO + CO_2$) and the combustion of fossil fuels to achieve the clinkering temperature of 1,450°C (2,640°F). Approximately 1*kg* of CO_2 is produced for each 1*kg* of clinker although the precise amount varies depending on the fuel efficiency of the plant. It is estimated that cement production accounts for approximately 5% of the CO_2 produced globally. Reducing the clinker content of cement by 10% will effectively reduce the CO_2 emissions associated with its production by the same amount. Of course, further reductions are possible by adding SCM (such as fly ash, slag, or natural pozzolans) either directly to the cement (blended cements) or by partially replacing cement with SCM at the concrete mixer.

This paper presents data from the three paving trials that were conducted in Quebec, Alberta, and Nova Scotia in 2008 and 2009. In two of the trials, concrete mixtures were produced with both PC

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Note: Submitted March 2, 2010; Revised April 30, 2010; Accepted June 30, 2010.

Table 1. CSA Nomenclature for the Cementitious Materials Used in this Study.

Type	Description	ASTM Equivalent Material
GU	"General Use" PC	ASTM C 150 Type I
GUL	"General Use" PLC	ASTM C 1157 Type GU
GUb	"General Use" blended hydraulic cement	ASTM C 595 Type IS
GULb	"General Use" blended limestone cement	ASTM C 1157 Type GU
F	Fly ash with low calcium content (< 8% CaO)	ASTM C 618 Class F fly ash
CI	Fly ash with intermediate calcium content (8-20% CaO)	ASTM C 618 Class F fly ash
S	Ground granulated blast furnace slag	ASTM C 989

Fig. 1. Photographs of Paving Trials in Quebec (Left), Alberta (Center), and Nova Scotia (Right).

and PLC and varying amounts of SCM. In the third trial, concrete mixtures were produced with blended cement containing PC + 15% slag or PLC + 15% slag, and varying amounts of fly ash were incorporated at the concrete mixer. The concrete mixes were tested to determine the setting characteristics, strength development, and durability including freeze-thaw, deicer-salt scaling, and chloride permeability.

Details of Field Trials

The three trial paving projects were located in Quebec, Alberta and Nova Scotia; photographs of the three sites are shown in Fig. 1. Details of the cementing materials and concrete mixtures used at the three sites are presented in Tables 1 to 3. Note that this paper uses the nomenclature from CSA A3001 for the cementing materials.

All three projects were placed in the fall (2008 or 2009), and the pavements are exposed to frequent applications of deicing salt, cyclic freezing and thawing, and heavy truck traffic (either cement tankers or ready-mixed concrete trucks).

Paving Slab at Gatineau Ready-Mixed Concrete Plant, Quebec

The first field trial was conducted using PLC with 12% interground limestone produced in Lafarge's Bath cement plant in Ontario. A total of eight concrete mixtures were produced, four with PLC and four with PC from the same plant. The total cementitious materials content of all mixtures was 355kg/m^3 (598lb/yd^3) and the water-to-cementing-materials ratio was W/CM = 0.44 to 0.45. A blended SCM (2 parts slag and 1 part fly ash) was added at the ready-mixed concrete plant at cement replacement levels of 0, 25, 40, and 50%. The concrete was used to construct a parking slab (4,500ft^2, 450m^2) at the concrete plant. The concrete was placed in October 2008. Extensive laboratory testing was conducted on specimens cast during the placing of the concrete and the results were recently reported in a previous paper [3]. In the PLC mix with 50% SCM, the clinker only constituted approximately 41 to 42% of the total mass of cementing materials. This compares with about 91 to 92% clinker for the control mix produced with PC and no SCM (PC contains approximately 3 to 4% limestone and 5% gypsum).

Pavement at Exshaw Cement Plant, Alberta

The second field trial was conducted using PLC produced at Lafarge's Exshaw cement plant in Alberta. The PLC was produced by intergrinding 12% limestone. This trial also incorporated four concrete mixes with PLC and four with PC, with fly ash being added

Table 2. Chemical Composition (%) of Cementing Materials Used in Field Trials.

Location of Trial	Cement Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2Oe	SO_3	LOI	Blaine (m^2/kg)
Quebec[1]	GU[2]	20.53	4.63	2.77	62.7	2.48	0.21	3.23	2.26	373
	GUL[3]	19.23	4.4	2.64	61.45	2.41	0.20	3.4	5.25	453
	CI	36.53	19.39	5.27	18.62	4.92	5.69	2.06	0.30	
	S	35.75	9.72	0.50	35.66	13.05	0.33	2.93	-	
Alberta	GU[2]	20.17	4.31	2.65	61.48	4.48	0.62	2.79	2.86	399
	GUL[3]	18.76	4.04	2.47	61.05	4.29	0.55	2.58	5.77	510
	CI	56.4	24.1	3.5	10.0	1.1	3.14	0.2	0.26	
Nova Scotia	GUb[4]	22.9	5.9	1.9	59.3	3.2	0.89	4.10	0.6	453
	GULb[5]	22.4	5.7	1.8	57.1	3.4	0.85	3.96	6.15	532
	F	48.02	20.65	7.92	6.68		1.48*	3.08	1.43	

Notes toTable

[1]In the Quebec trial the SCM used was a pre-blended SCM consisting of two parts Type S slag with one part Type CI fly ash.
[2]Type GU cement used in Quebec and Alberta contains 3-4% limestone and 91% clinker
[3]Type GUL cement used in Quebec and Alberta contains 12% limestone and 83% clinker
[4]Type GUb cement used in Nova Scotia contains no limestone, 15% slag and 80% clinker
[5]Type GULb cement used in Nova Scotia contains 12% limestone, 15% slag and 68% clinker
All proportions expressed in notes above are approximate and are based on gypsum content of 5%
*Available alkali reported (ASTM C 311) not total alkali

Table 3. Details of Concrete Mixes Used in Field Trials (1kg/m^3 = 1.686lb/yd^3).

Location of Trial	SCM (%, Type)	Cement Type	W/CM	Slump (*mm*)	Air (%)	Set Time (*min.*)	Cementing Material (kg/m^3)	Clinker Content (kg/m^3)
Quebec	0	GU	0.45	100	6.8		355	323
		GUL	0.44	80	6.0		355	295
	25 CI/S	GU	0.44	75	6.2		355	242
		GUL	0.45	100	6.6		355	221
	40 CI/S	GU	0.44	95	6.8		355	194
		GUL	0.44	80	6.0		355	177
	50 CI/S	GU	0.44	95	6.8		355	162
		GUL	0.44	95	6.5		355	147
Alberta	0	GU	0.42	125	7.8	330	410	373
		GUL	0.42	120	6.8	345	410	340
	15 CI	GU	0.40	135	6.2	396	410	321
		GUL	0.40	100	6.0	378	410	289
	25 CI	GU	0.38	115	6.4	451	410	280
		GUL	0.38	95	6.3	403	410	255
	30 CI	GU	0.37	120	6.1	468	410	261
		GUL	0.37	115	6.4	442	410	238
Nova Scotia	0	GUb	0.42	75	5.8		392	298
		GULb	0.44	60	6.6		384	261
	15 F	GUb	0.43	80	6.1		384	248
		GULb	0.43	65	6.2		385	222
	20 F	GUb	0.44	65	6.6		385	234
		GULb	0.43	75	6.5		386	210

at the ready mix plant at levels of 0, 15, 25, and 30%. The total cementitious materials content of all mixtures was 410kg/m^3 (691lb/yd^3) and the water-to-cementing-materials ratio was W/CM = 0.37 to 0.42. These concrete mixtures were used for paving but additional PC and PLC mixtures were also produced for two retaining walls and a section of slipformed curb. The concrete was placed in September, 2009. The pavement was 0.30 to 0.45*m* thick and was reinforced with a single mat of reinforcement. The concrete was placed by pump, struck off, bull floated, and tined. After finishing, the surface was treated with an evaporation retarder as it was windy. Finally, a curing membrane was applied.

Pavement at Brookfield Cement Plant

The third field trail was conducted using blended Portland limestone cement produced by intergrinding 12% limestone and 15% slag granules together with the Portland cement clinker and gypsum at Lafarge's Brookfield cement plant in Nova Scotia. The

Table 4. Summary of Test Results from Paving Trial in Quebec.

	0% SCM		25% SCM		40% SCM		50% SCM	
	PC	PLC	PC	PLC	PC	PLC	PC	PLC
Compressive Strength, ASTM C 39, *MPa*, (1*MPa* = 145*psi*)								
3 Days	24.2	25.2	21.7	20.7	18.9	19.2	15.3	15.6
7 Days	30.2	30.5	29.8	29.6	30.3	31.1	29.4	28.8
28 Days	37.7	38.2	41.3	39.8	43.5	43.5	43.0	42.5
56 Days	41.3	40.9	45.4	44.7	48.6	48.3	48.7	46.5
Cores at 35 Days	39.7	35.3	35.7	35.5	42.3	43.2	37.6	39.4
Rapid Chloride Permeability Test, ASTM C 1012, Coulombs								
28 Days	3446	3734	2004	1765	1145	1056	1052	932
56 Days	2781	2964	1233	1317	733	666	548	474
Cores at 35 Days	2395	2345	1410	1308	570	617	491	520
Bulk Diffusion Coefficient*, ASTM C 1556, x $10^{-12} m^2/s$ (1 x $10^{-12} m^2/s$ = 0.00124 x in^2/y)								
40 Days in NaCl	15	11.9	3.77	2.91	1.51	1.22	1.25	1.81
Freeze-Thaw Durability Factor, ASTM C 666, %								
300 Cycles	101	100	101	104	101	103	102	100
Deicer-Salt Scaling Mass Loss, ASTM C 672, g/m^2 (1g/m^2 = 0.029oz/yd^2)								
50 Cycles	40	10	30	50	80	230	400	320

*The bulk diffusion test was performed on cores extracted from the pavement at 35 days.

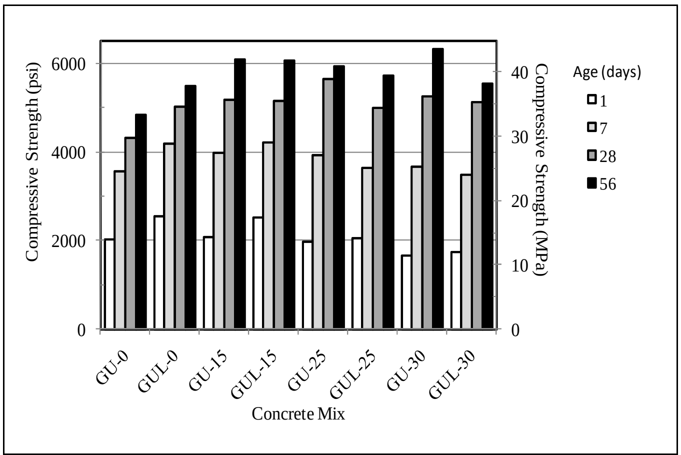

Fig. 2. Strength Results for Concrete Mixtures Used in Alberta Paving Trial.

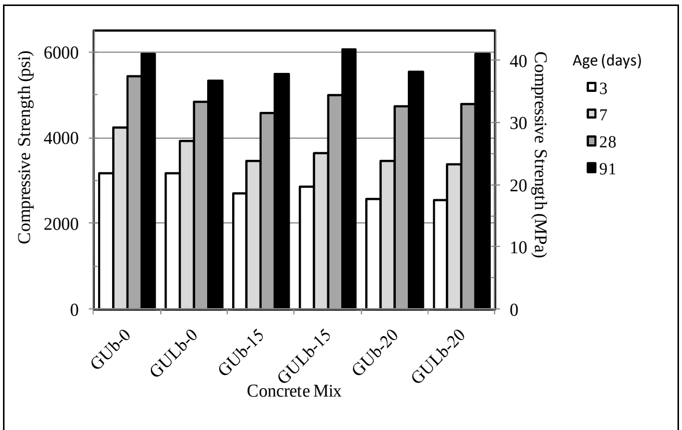

Fig. 3. Strength Results for Concrete Mixtures Used in Nova Scotia Paving Trial.

performance of this cement was compared with a similar blended Portland cement produced with 15% slag and no limestone. Six concrete mixes were produced with these two cements with fly ash being added at the concrete plant at replacement levels of 0, 15, and 20% fly ash. The total cementitious material's content of the concrete mixtures was 384 to 392kg/m^3 (647 to 661lb/yd^3) and the water-to-cementing-material's ratio was W/CM = 0.42 to 0.44. The concrete was used to pave the roadway outside the main entrance of the cement plant and was placed in October 2009. The pavement was 0.30*m* thick, transverse joints were saw cut (no dowels), and the longitudinal joint between the two lanes was dowelled. Placing was carried out using a deck finishing machine and the surface was bull floated, broom textured, and sprayed with a curing membrane.

Test Results

The results of the tests conducted on the concrete for the paving slab in Quebec have been reported in detail elsewhere [3], and a summary is provided in Table 4. The results from this trial show significant improvements in the long-term strength and the resistance to chloride ion penetration as the SCM content of the concrete increases. However, at a given level of SCM, there is no consistent difference between the performances of the concrete with PLC versus PC. The paving slab has now been through two winters, and there are no signs of deicer salt scaling for any of the mixes even when the Portland cement clinker represented less than 45% of the total cementing material. This confirms the satisfactory performance of these mixes in laboratory deicer salt scaling tests [3] and is encouraging as it demonstrates that PLC can be used with high levels of SCM (50% in this case) without compromising durability.

For all three trials, the concrete mixes with PLC generally required more air-entraining admixture than equivalent mixes with PC. No noticeable differences were observed in the water demand and placing characteristics of similar concrete mixes produced with either PC or PLC; however, mixes with PLC appeared to have higher paste content and were easier to finish. Set times were only

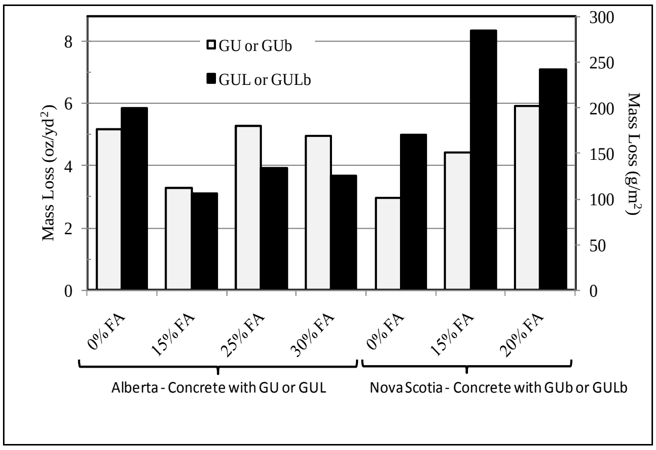

Fig. 4. Scaling Results (ASTM C 672) for Concrete Mixtures Used in Alberta and Nova Scotia Paving Trials.

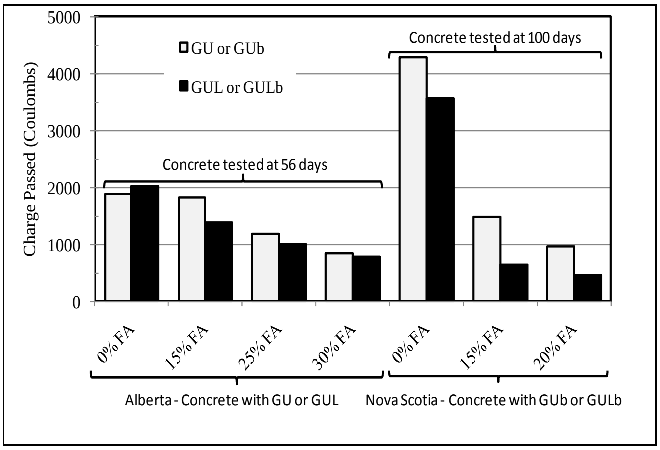

Fig. 5. Rapid Chloride Permeability Results (ASTM C 1012) for Concrete Mixtures Used in Alberta and Nova Scotia Paving Trials.

measured for the concretes mixtures used for the Alberta trial (see Table 3). The use of PLC resulted in a slightly accelerated set for the three fly ash mixes, but a slight retardation for the mix without fly ash. Laboratory studies generally indicate a significant reduction in the set time for concrete produced with PLC [1].

Figs. 2 and 3 show the strength development of site-cast cylinders from the trials in Alberta and Nova Scotia, respectively. An increase in the one-day strength was observed in the PLC concretes in Alberta, but later-age tests showed no consistent differences between the strength of similar mixes produced with either PC or PLC at either location.

Fig. 4 shows the results of salt scaling tests (ASTM C 672) for the trial mixes used in Alberta and Nova Scotia. All the results were satisfactory being well below the typical limits used by transportation agencies in Canada (maximum mass loss in the range of 800 to 1,000g/m^2 or 23 to 29oz/yd^2 after 50 cycles). Slightly greater mass losses were observed in the three concretes produced with the PLC-slag blend in the Nova Scotia trial; however, the differences are small, being less than 100g/m^2 (3oz/yd^2).

Results from rapid chloride permeability tests (ASTM C 1202) are shown in Fig. 5. As expected the addition of fly ash reduced the charge passed in all cases. No consistent trend was observed with PLC for the results from Alberta, but all three concretes produced with the PLC-slag blend in Nova Scotia showed lower amounts of charge passed than comparable mixes with the PC-slag blend. The control mixes without fly ash for both trials produced slightly unexpected "permeability" results. Values in the range of 2000 coulombs for the PC and PLC mixes without fly ash are lower than expected for concrete that does not contain any supplementary cementing material and W/CM = 0.42. Conversely, values in the range of 3,500 to 4,200 coulombs are high for concrete containing blended cement with 15% slag when tested at 100 days.

Discussion

These trials demonstrate that concrete produced with PLC with up to 12% limestone interground with the clinker provides the same level of performance as concrete produced with PC with approximately 3.5% limestone. In addition, the performance of fly ash concrete is not adversely affected by using PLC instead of PC. The data presented from the trials in Alberta and Nova Scotia together with the previously published data from the trial in Quebec demonstrate that very substantial reductions in the amount of cement clinker used in concrete (see Table 3) can be achieved through the combined use of PLC and SCM without necessarily jeopardizing concrete performance. Using PLC with relatively high amounts of SCM (such as 40% or as 50% used in Quebec trial) can result in reductions in the clinker content of paving mixes in the range of 145 to 175kg/m^3 (240 to 290lb/yd^3). Since the manufacturer of Portland cement clinker results in approximately 1-kg of CO_2 for every 1-kg of clinker[1], the reductions in the clinker content of the concrete can be translated directly into reductions in the CO_2 footprint of the concrete. This translates to more than a 1-tonne (1.1 short ton) reduction of CO_2 for every 8-m^3 truckload of concrete.

Of course it is not always possible to use such high levels of SCM. The slower strength gain of many SCMs will limit the amount that can be used in many applications where the speed of construction is critical, especially in cold weather. Also, concerns over deicer-salt scaling in hand-finished flatwork such as sidewalks and scaling may also limit the amount of SCM that is used. However, even when the SCM content is limited to 15 to 25%, the combined use of PLC and SCM can realize clinker savings in the range of 75 to 120kg/m^3 (125 to 200lb/yd^3) in paving mixes.

The blended PLC-slag cement (Type GULb) used in Nova Scotia gives equivalent performance to the PC-slag blend (Type GUb), which, in turn, performs in a similar manner to straight PC cement (Type GU) when the level of slag is limited to 15%. The clinker content of the Type GULb is just 68% as compared with 91% for typical Type GU cement. It is feasible that most, if not all, of the Type GU cement (equivalent to ASTM C 150 Type I) used today could be replaced by Type GULb cement produced with interground limestone and a low to moderate level of SCM. This would result in

[1] It should be noted that the 1-kg CO_2 per 1-kg clinker is an approximation. Approximately, half of this amount results from the calcination of limestone. The remainder results from the combustion of fuel. Consequently, the total amount of CO_2 varies depending on the energy efficiency of the cement plant and the fuels used. Modern plants with preheater/precalciner towers will produce less than 1-kg CO_2 per 1-kg of clinker.

very substantial reductions in the CO_2 emissions associated with the concrete industry. Of course, further reductions could be achieved by the partial replacement of the Type GULb by SCM at the concrete plant on a case-by-case basis.

Conclusions

This paper describes three field trials where PLC has been used in pavement construction. The following conclusions can be drawn from the study:

1. PLC can be produced with up to 15% interground limestone to achieve equivalent performance to PC.
2. Equivalent performance is achieved by intergrinding the limestone with the clinker and gypsum to a Blaine fineness approximately 100m^2/kg higher than ordinary PC produced from the same clinker.
3. Concretes produced with PLC had slightly shorter set times and increased 1-day strengths compared to similar concretes produced with PC produced from the same clinker. Strengths at later ages were generally similar.
4. Durability properties measured included resistance to chloride ion penetration, freezing and thawing, and deicer-salt scaling. The introduction of fly ash, added at the ready-mixed concrete plant, significantly influenced the durability results, but there were no consistent differences between the performances of the concrete produced with PLC or PC at the same fly ash content.

A blended PLC containing 15% ground granulated blast furnace slag and 12% limestone was produced and provided the same performance as a blended PC with 15% slag and a plain PC produced from the same clinker. The blended PLC contained just 68% clinker as compared with 91% clinker for the plain PC.

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