Optimum Slab-on-Ground Concrete

Lowering the water content of a minimized paste volume reduces curling

by Daniel M. Vruno and Michael J. Ramerth

The Minnesota Concrete Council (MCC) is dedicated to advancing education, technical practice, scientific investigation, and research in the field of cast-in-place construction by organizing the efforts of its diverse membership as a nonprofit public service. The MCC and Target Corporation recently teamed together to gain pertinent knowledge about optimizing concrete proportioning to minimize curling, maximize finishability, and improve sustainability. This article summarizes the research. The work consisted of a 2^3 factorial statistical design laboratory phase and a 656 yd^3 (500 m^3) field placement phase. This approach allows the reader to judge the performance of the developed mixtures through both the laboratory and field phases.

Laboratory Phase

Independent variables

A total of 13 concrete mixtures were included in the laboratory phase. Each mixture contained a well-graded blend of five aggregates ranging from 1-1/2 in. (38 mm) gravel to sand. The grading followed the "8-18 rule,"[1] with 8 to 18% of the combined aggregate retained on each standard sieve below the top size sieve and above the No. 100 (149 µm) sieve (refer to Fig. 1 for details). Three independent variables—water-cementitious material ratio (*w/cm*), total cementitious material content, and cement replacement levels—were considered at two levels (Table 1 and Fig. 2 and 3). (Detailed information on the composition of the concrete mixtures is provided with the online version of this article.)

The 11 mixtures included in the factorial study contained supplementary cementitious materials (SCMs). Mixtures 5 and 12 were not part of the factorial study, but they provided baseline data for a 100% portland cement mixture.

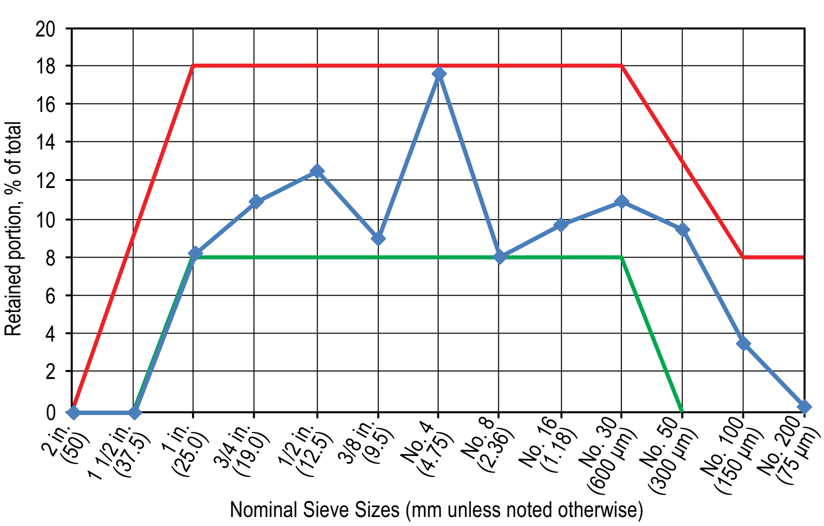

Fig. 1: Aggregate grading was achieved using a blend of five aggregates and followed the Shilstone "8 to 18 rule"

Dependent variables

The dependent variables (that is, responses) included the performance criteria of setting times, shrinkage, and finishability. Setting times were determined per ASTM C403/C403M, Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance. Shrinkage (length change) was measured per ASTM C157/C157M, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. Finishability was subjectively evaluated by three concrete finishers who applied a float finish to a test slab measuring 24 x 24 x 4 in. (610 x 610 x 102 mm). Each finisher used magnesium and wood floats and rated finishability using the following scale: 1—very difficult, 2—difficult, 3—moderate, 4—easy, and 5—very easy.

Results

The laboratory results are summarized in Table 2 and Fig. 4 and 5. Setting times for the factorial points are summarized in Fig. 4, with

Table 1:
Independent variables for the 13 concrete mixture designs studied in the laboratory phase

Mixture No.	*w/cm*	Total cementitious material content, lb/yd³ (kg/m³)	Cement replacement, % and type
1	0.45	520 (308)	40 fly ash
2	0.45	480 (285)	20 fly ash + 20 slag cement
3	0.45	480 (285)	40 fly ash
4	0.475	520 (308)	40 fly ash
5	0.45	520 (308)	—
6	0.45	520 (308)	20 fly ash + 20 slag cement
7	0.45	500 (297)	20 fly ash + 20 slag cement
8	0.50	520 (308)	40 fly ash
9	0.50	520 (308)	20 fly ash + 20 slag cement
10	0.50	480 (285)	40 fly ash
11	0.50	480 (285)	20 fly ash + 20 slag cement
12	0.50	480 (285)	—
13	0.50	500 (297)	40 fly ash

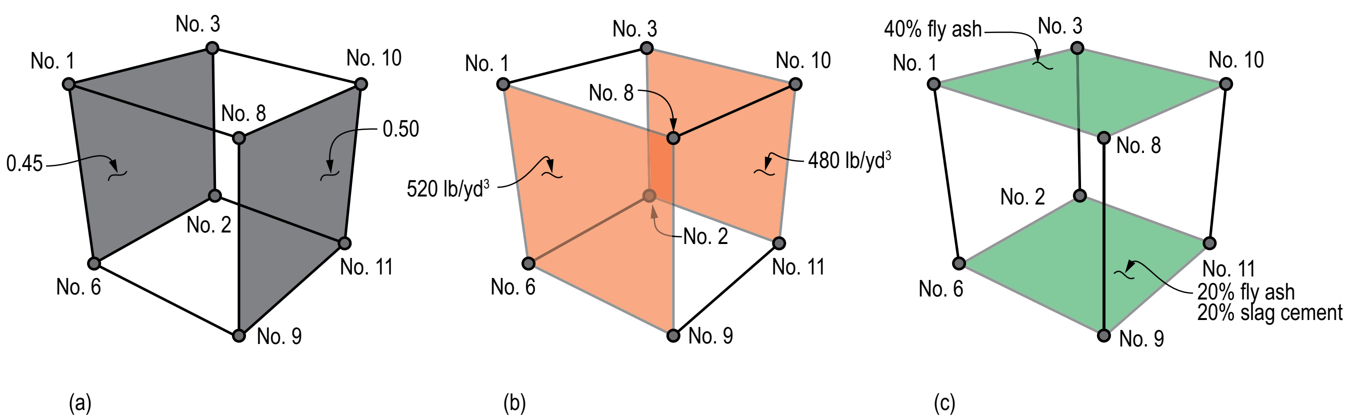

Fig. 2: Factorial points for the independent variables included: (a) *w/cm* values of 0.45 and 0.50; (b) cementitious material contents of 480 and 520 lb/yd³ (285 and 308 kg/m³); and (c) cement replacements of 40% fly ash and 20% fly ash plus 20% slag cement

red factorial points highlighting the fact that mixtures with 40% fly ash cement replacement had somewhat longer setting times than mixtures with 20% fly ash and 20% slag cement, with an exception of Mixture 9. Shrinkage (% length change) results are presented in Fig. 5, with red factorial points indicating mixtures with shrinkage exceeding 0.030%. The results listed in Table 2 indicate that within each *w/cm* group (0.45 and 0.50), the mixtures with 520 lb/yd³ (308 kg/m³) total cementitious material shrunk slightly more than the mixtures with 480 lb/yd³ (285 kg/m³) total cementitious material.

For the mixtures with *w/cm* of 0.45, finishability was rated as 2—difficult and 3—moderate for the mixtures with 480 lb/yd³ (285 kg/m³) and 520 lb/yd³ (308 kg/m³) total cementitious material, respectively (Table 2). For the mixtures with *w/cm* of 0.50, finishability ranged from 2—difficult to 3—moderate for the mixtures with 480 lb/yd³ (285 kg/m³) total cementitious material, and from 3—moderate to 4—easy for two mixtures with 520 lb/yd³

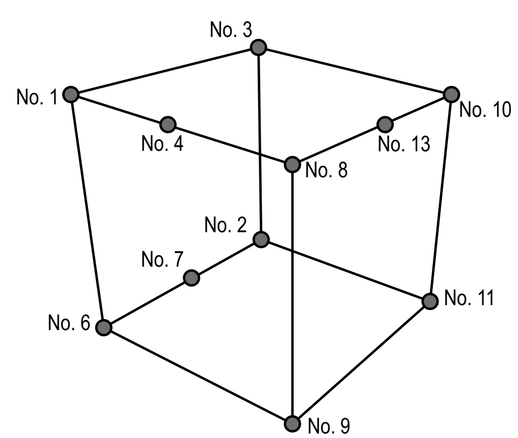

Fig. 3: Factorial and center points investigated for the study. Mixtures 4, 7, and 13 were included in the study to check the significance of curvature. Note that Mixtures 5 and 12 had zero cement replacement (100% portland cement mixtures) and are, therefore, not shown

Table 2:
Summary of results from laboratory phase

	Independent variables			Dependent variables		
Mixture No.	*w/cm*	Total cementitious material, lb/yd³ (kg/m³)	Cement replacement, % and type	Setting times: initial and final, hr:min	Shrinkage (length change), %	Finishability rating
1	0.45	520 (308)	40 fly ash	7:40 10:40	0.030	3
2	0.45	480 (285)	20 fly ash + 20 slag cement	6:37 9:35	0.025	2
3	0.45	480 (285)	40 fly ash	7:50 10:04	0.027	2
4	0.475	520 (308)	40 fly ash	7:49 10:38	0.032	3
5	0.45	520 (308)	None	7:03 8:48	0.033	2
6	0.45	520 (308)	20 fly ash + 20 slag cement	7:20 9:52	0.031	2
7	0.45	500 (297)	20 fly ash + 20 slag cement	7:16 9:50	0.027	2
8	0.50	520 (308)	40 fly ash	7:58 10:22	0.034	4
9	0.50	520 (308)	20 fly ash + 20 slag cement	7:38 10:45	0.033	3
10	0.50	480 (285)	40 fly ash	7:47 10:30	0.030	3
11	0.50	480 (285)	20 fly ash + 20 slag cement	7:02 9:30	0.029	2
12	0.50	480 (285)	None	5:14 7:08	0.031	2
13	0.50	500 (297)	40 fly ash	7:49 10:24	0.031	3

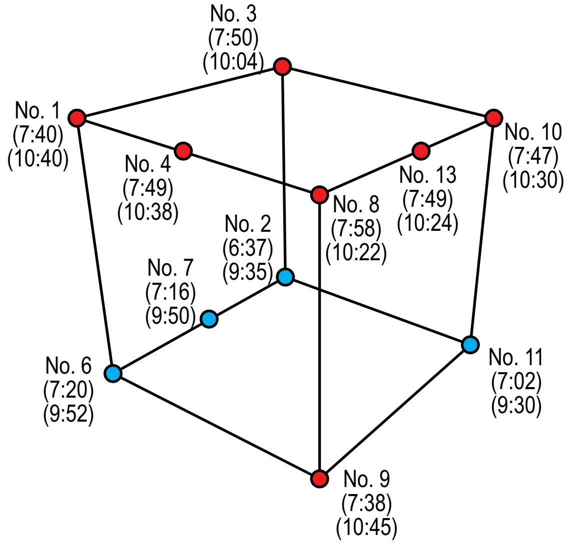

Fig. 4: Initial and final setting times for the laboratory mixtures. Red circles indicate mixtures with initial and final setting times exceeding 7.5 or 10 hours, respectively

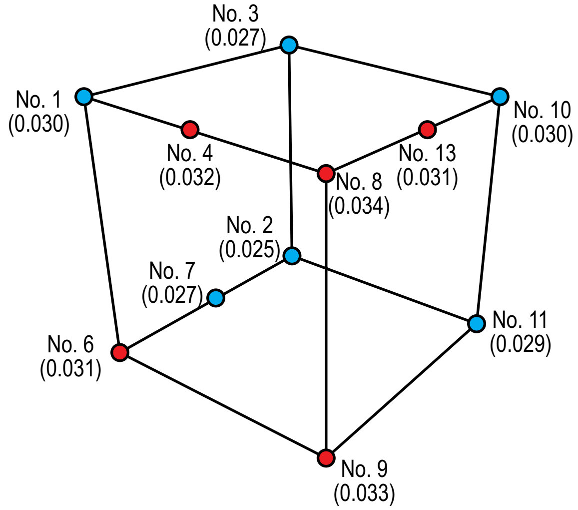

Fig. 5: Shrinkage (% length change) for the laboratory mixtures. Red circles indicate shrinkage exceeding 0.030%

(308 kg/m³) total cementitious material. Finally, mixtures with 40% fly ash replacement were generally reported to be easier to finish than mixtures with combined 20% fly ash and 20% slag cement replacement.

Field Phase

Independent variables

Based on our analysis of the laboratory results, we selected four of the 13 laboratory concrete mixtures (Mixtures 2, 6, 10, and 11) for evaluation in a field study involving a slab-on-ground placement for a Target store in Inver Grove Heights, MN. The four mixtures were placed on January 31, 2012 (Fig. 6). One mixture was used in each of four 105 x 100 ft (32 x 30.5 m) sections in a 420 x 100 ft (128 x 30.5 m) strip in the middle of the store. The concrete quantity required for each section was 164 yd³ (125 m³).

Dependent variables

The three dependent variables (setting time, shrinkage, and finishability) examined in the laboratory study were also evaluated during the field study, using the same procedures as in the laboratory phase. The results of these tests are listed in Table 3.

Fig 6: Placement of the slab-on-ground floor for the Target store in Inver Grove Heights, MN, on January 31, 2012

The results indicate that the mixtures with *w/cm* of 0.5 had somewhat shorter setting times than the mixtures with *w/cm* of 0.45. Length change (shrinkage) for all mixtures did not exceed 0.030%. Very difficult finishability was observed for Mixture 2 with *w/cm* of 0.45, 480 lb/yd³ (285 kg/m³) total cementitious material, and 20% fly ash and 20% slag cement replacement.

Table 3:
Summary of results from field phase

	Independent variables			Dependent variables		
Mixture No.	w/cm	Total cementitious material, lb/yd³ (kg/m³)	Cement replacement, % and type	Setting times: initial and final, hr:min	Shrinkage (length change), %	Finishability rating
2	0.45	480 (285)	20 fly ash + 20 slag cement	7:55 10:45	0.027	1
6	0.45	520 (308)	20 fly ash + 20 slag cement	7:22 10:32	0.030	3
10	0.50	480 (285)	40 fly ash	7:08 9:58	0.028	3
11	0.50	480 (285)	20 fly ash + 20 slag cement	5:36 8:25	0.029	3

Table 4:
Summary of F_F and F_L numbers and curling for the four mixtures

	Average F-numbers				Curling (50 days), in.
	Initial, 1 day		Final, 50 days		
	F_F	F_L	F_F	F_L	
Mixture 2	62.4	57.9	51.7	52.0	5/16
Mixture 11	61.6	39.4	40.8	34.5	5/16
Mixture 6	84.6	51.1	45.3	51.2	5/16
Mixture 10	68.8	41.2	42.9	38.4	5/16

1 in. = 25 mm

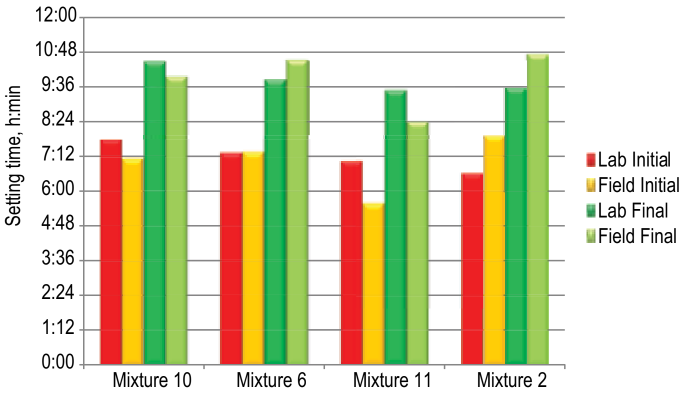

Fig. 7: Comparison of setting times achieved in the laboratory and field phases of the study

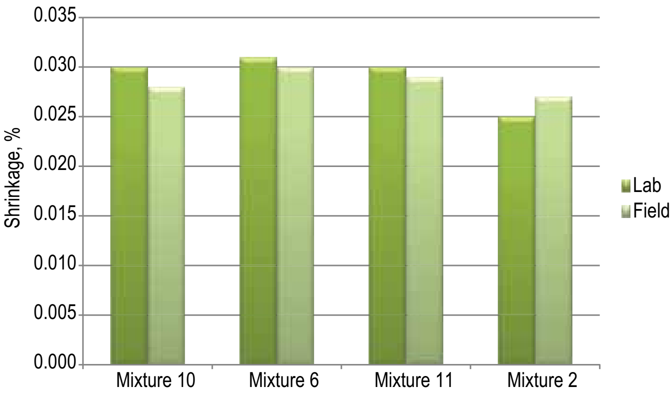

Fig. 8: Comparison of shrinkage achieved in the laboratory and field phases of the study

Flatness, levelness, and curling

ACI 117-06, Section 4.8.5.1,[2] provides floor surface classification based on the specified overall values of flatness (SOF_F) and levelness (SOF_L). Flatness and levelness values are determined in accordance with ASTM E1155, Standard Test Method for Determining F_F Floor Flatness and F_L Floor Levelness Numbers. Higher flatness numbers (F_F) indicate a flatter floor and higher levelness numbers (F_L) indicate a more level floor. Both the flatness and levelness will typically decrease with time as the concrete shrinks and curls.

F_F and F_L evaluations were performed during the field phase using a Face Construction Technologies Dipstick Profiler at 1 day and 50 days after concrete placement. The measurement results are listed in Table 4. Based on the test results after 50 days and the difference between the 1-day and 50-day results, Mixture 2 provided the best average flatness and levelness.

The saw-cut joint spacing for the subject slab was typically 10 ft 7 in. x 10 ft 9 in. (3.2 x 3.3 m). Curling was measured at six saw-cut joints at each of the four test sections for a total of 24 readings. Measurements were made using a 10 ft (3 m) straightedge at 50 days after placement. The curling at each of the 24 measured locations was consistently 5/16 in. (8 mm), with no evident difference among the four mixtures.

Discussion of Results

Mixtures 5 and 12 (100% portland cement mixtures) set faster than the other mixtures, experienced shrinkage (length change) greater than 0.03%, and had a low finishability rating of 2—difficult.

In the laboratory, we had control over many parameters that eluded our control in the field. As can be seen in Fig. 7, setting times varied significantly. The initial setting time for Mixture 2, for example, was considerably longer in the field than in the laboratory. In addition, although Mixture 2 had the shortest initial setting time in the laboratory phase, it had the longest initial setting time among the four mixtures placed in the field.

In addition, Mixtures 2 and 11, when tested in the lab, had the shortest final setting times in comparison with the other mixtures with SCMs. Nevertheless, during testing in the field, Mixture 2 had the longest final setting time, while Mixture 11 remained the fastest to set.

As was previously noted, the field placement occurred on a January day in Minnesota; the cold weather almost certainly was a major factor affecting the setting times. In winter placements, the ingredients that typically are heated at concrete plants are the sand and water. For each 10 yd^3 (7.7 m^3) load of concrete, mixtures with a *w/cm* of 0.45 will have 240 lb/yd^3 (142 kg/m^3) less heated water than mixtures with a *w/cm* of 0.50. Also, a portion of the volume of that amount of water is replaced with an equivalent volume of unheated (cold) aggregate. Finally, it's important to note that Mixture 2 was used in the placement located closest to the truck entrance. That portion of the slab therefore experienced the coolest curing temperatures.

As can be seen in Fig. 8, Mixture 2 had the lowest shrinkage out of four mixtures evaluated in the laboratory and in the field. When tested in the lab, the finishability of Mixture 2 was comparable to Mixtures 6 and 11 and rated as 2—difficult (Table 2). While in the field, out of the four tested mixtures, the finishability of Mixture 2 worsened and had the lowest rating of 1—very difficult (Table 3).

Conclusions

The data presented in Table 2 indicate the following relative effects for the evaluated mixtures:

- A lower *w/cm* combined with a lower total cementitious material content slightly lowers the shrinkage and reduces finishability;
- A lower *w/cm* combined with a higher total cementitious material content results in greater shrinkage, no improvement in setting times, and slight improvement in finishability;
- A higher *w/cm* combined with a lower total cementitious material content slightly lowers the shrinkage and improves setting times and finishability; and

- A higher *w/cm* combined with a higher total cementitious material content results in greater shrinkage, longer set times, and slightly better finishability.

Although the plain portland cement mixtures had faster setting times, shrinkage was increased and finishability was reduced relative to mixtures with SCMs.

An optimum slab-on-ground mixture design should minimize curling and maximize finishability. Based on these criteria, we judged Mixture 11 to be the optimum mixture for a slab-on-ground concrete. This mixture had a *w/cm* of 0.5 and a total cementitious material content of 480 lb/yd^3 (285 kg/m^3), the fastest setting time, shrinkage below 0.03%, and finishability rating of 3—moderate.

References

1. Shilstone, J.M. Sr., "Concrete Mixture Optimization," *Concrete International*, V. 12, No. 6, June 1990, pp. 33-39.

2. ACI Committee 117, "Specifications for Tolerances for Concrete Construction and Materials and Commentary (ACI 117-06)," American Concrete Institute, Farmington Hills, MI, 70 pp.

Note: Additional information on the ASTM standards discussed in this article can be found at www.astm.org.

Selected for reader interest by the editors.

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Summary of concrete mixture designs used for the study. Aggregates are in saturated surface dry (SSD) condition

Mixture no.	**1**	**2***	**3**	**4**	**5**	**6***	**7**	**8**	**9**	**10***	**11***	**12**	**13**
Description													
Cement, type I, lb/yd^3 (kg/m^3)	312 (185)	288 (170)	288 (170)	312 (185)	520 (309)	312 (185)	300 (178)	312 (185)	312 (185)	288 (171)	288 (171)	480 (285)	300 (178)
Class C fly ash, lb/yd^3 (kg/m^3)	208 (123)	96 (57)	192 (113)	208 (123)	—	104 (62)	100 (59)	208 (123)	104 (62)	192 (113)	96 (57)	—	200 (119)
Slag cement, lb/yd^3 (kg/m^3)	—	96 (57)	—	—	—	104 (62)	100 (59)	—	104 (62)	—	96 (57)	—	—
No. 4 gravel, lb/yd^3 (kg/m^3)	664 (394)	685 (406)	682 (404)	659 (391)	674 (400)	669 (397)	676 (401)	649 (385)	653 (387)	669 (397)	670 (397)	675 (400)	660 (392)
No. 89 gravel, lb/yd^3 (kg/m^3)	796 (472)	819 (486)	817 (485)	788 (468)	806 (478)	801 (475)	810 (481)	779 (462)	782 (464)	803 (476)	805 (478)	810 (481)	790 (469)
No. 6 gravel, lb/yd^3 (kg/m^3)	697 (413)	719 (426)	717 (425)	690 (409)	705 (418)	700 (415)	708 (420)	683 (405)	685 (406)	701 (416)	705 (418)	710 (421)	691 (410)
Concrete sand, lb/yd^3 (kg/m^3)	996 (591)	1025 (608)	1022 (606)	986 (585)	1010 (599)	1000 (593)	1013 (601)	976 (579)	980 (581)	1002 (594)	1004 (596)	1015 (602)	990 (587)
Grit sand, lb/yd^3 (kg/m^3)	166 (98)	170 (100)	172 (102)	163 (97)	168 (100)	167 (99)	168 (100)	163 (97)	163 (97)	168 (100)	168 (100)	170 (100)	165 (98)
Mid-range water-reducing admixture, fl oz (ml)	21 (621)	19 (562)	19 (562)	25 (739)	21 (621)	21 (621)	23 (680)	—	—	—	—	—	—
Water, lb/yd^3 (kg/m^3)	234 (138)	216 (128)	216 (128)	247 (147)	234 (138)	234 (138)	225 (133)	260 (154)	260 (154)	240 (142)	240 (142)	240 (142)	250 (148)
w/cm	0.45	0.45	0.45	0.475	0.45	0.45	0.45	0.50	0.50	0.50	0.50	0.50	0.50
Mortar fraction, %	53	51	52	54	52	53	52	54	53	52	52	52	53

*Mixtures investigated in both laboratory and field phases

Cement: Holcim, St. Genevieve, ASTM C150

Fly ash: Lafarge, Portage, ASTM C618

Slag cement: Holcim, STGMLMO 100, ASTM C989

Aggregate: Aggregate Industries, ASTM C33

Mid-range water-reducing admixture: BASF Polyheed 997, ASTM C494