ABRASION RESISTANCE OF HIGH-STRENGTH CONCRETE MADE WITH CLASS C FLY ASH

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Synopsis: This work was undertaken to evaluate the abrasion resistance of concrete proportioned to have five levels of cement replacements (15, 30, 40, 50, and 70%) with one source of Class C fly ash. A reference concrete without fly ash was proportioned to have the 28-day compressive strength of 41 MPa. Concrete specimens were subjected to abrasion according to the ASTM C-944 test method. In this work, all the concretes made with and without fly ash passed the abrasion resistance requirements per ASTM C-779, Procedure C. Depth of wear values produced by the ASTM C-944 test, were quite low (less than 1 mm) for the strength levels tested in this work.

An accelerated test method was developed and used to evaluate abrasion resistance of high-strength concrete. This method used the grinding wheels with smaller size washers, and a standard Ottawa sand was applied to the surface being abraded at an interval of one minute. The accelerated test results showed that abrasion resistance of concrete having cement replacement up to 30% was comparable to the reference concrete without fly ash. Beyond 30% cement replacement, the fly ash concrete exhibited slightly lower resistance to abrasion relative to the no-fly ash concrete.

Keywords: abrasion resistance; compressive strength; concretes; depth of wear; fly ash .

BIOGRAPHICAL SKETCH

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INTRODUCTION

Deterioration of concrete surfaces occurs due to various forms of wear such as erosion, cavitation, and abrasion due to various exposures. Abrasion wear occurs due to rubbing, scraping, skidding, or sliding of objects on the concrete surface. This form of wear is observed in pavements, floors, or other surfaces on which friction forces are applied due to relative motion between the surfaces and moving objects.

Concrete abrasion resistance is markedly influenced by a number of factors including concrete strength, aggregate properties, surface finishing, and type of hardeners or toppings. A large number of previous studies (1-6) have indicated that concrete abrasion resistance is primarily dependent upon compressive strength of the concrete. The factors such as air entrainment, water-to-cement ratio, type of aggregates and their properties, etc. that affect the concrete strength, therefore, should also influence abrasion resistance. According to ACI Committee 201, concrete subjected to abrasion should have at least 28 MPa compressive strength (1).

In general, hardened paste possesses low resistance to abrasion. In order to develop concrete for high abrasion resistance, it is desirable to use hard surface material, aggregate, and paste having low porosity and high strength (2).

Data on the abrasion resistance of concrete is needed to determine appropriate mixture proportions in order to make abrasion resistant concrete. A limited amount of published work is available on abrasion resistance of fly ash concrete, especially high-volume Class C fly ash concrete. Therefore, this project was undertaken to investigate abrasion resistance of concrete incorporating Class C fly ash.

RESEARCH SIGNIFICANCE

This research was carried out to evaluate the performance of Class C fly ash in concrete with respect to strength and abrasion resistance. Concrete strength and abrasion resistance were determined at various levels of cement replacements with the fly ash. The results obtained in this investigation would be useful in establishing mixture proportions for Class C fly ash concretes.

LITERATURE REVIEW

It is well established that cement content, water-to-cement ratio, slump, air content, type of finish, and curing, affect the characteristics of the concrete surface layer including abrasion resistance (3). Numerous studies (4,5,6) have shown that compressive strength is the most important factor governing the abrasion resistance of concrete. Witte and Backstrom (5) reported that for equal strengths, abrasion resistance of air entrained concrete is similar to that of non-air entrained concrete. Concrete resistance to abrasion is strongly influenced by the relative abrasion resistance of its constituent materials such as coarse aggregates and mortar (6). Generally, concretes made with trap rock or granite as aggregates exhibit higher abrasion resistance compared to the "softer" limestone aggregate concretes.

A number of investigations have shown that both surface finishing techniques and types of curing practice have a strong influence on abrasion resistance of concrete (7-12). Nanni (13) indicated that compressive strength is a poor parameter to evaluate abrasion because of influence of surface finishing and curing conditions. In general, proper finishing and curing practices are known to enhance the abrasion resistance of concrete considerably.

Nanni (13) evaluated abrasion resistance of roller compacted concrete (RCC) using both laboratory and field specimens. Fifty percent of the cement was replaced by a Class C fly ash in his investigation. The results showed that: (1) testing under air-dry conditions produces approximately 30 to 50 percent less wear than under wet conditions; (2) the addition of fibers (synthetic and steel fibers) does not cause an appreciable change in abrasion resistance; and, (3) improper moist-curing conditions produce more negative effects on surface quality than on compressive strength. Liu (14) compared abrasion resistance of no-fly ash concrete with a fly ash concrete having 25% cement replacement. Abrasion resistance of concrete with or without fly ash was similar up to 36 hours of abrasion testing. However, beyond 72 hours of the testing, the fly ash concrete lost about 25% more weight than the no-fly ash concrete.

Gebler and Klieger (15) studied the abrasion resistance of concrete containing ten different sources of Class F and Class C fly ashes. Concrete mixtures were proportioned to have 25% fly ash by weight of total cementitious materials. The authors reported that the abrasion resistance of Class C fly ash concretes was generally superior to Class F fly ash concretes.

Tikalsky et al. (16) determined abrasion resistance of concrete having cement replacement in the range of 0-35% with Class F and Class C fly ashes. Concretes containing Class C fly ash performed better than both the plain portland cement concretes and the concretes containing Class F fly ash. Hadchti et al. (4) evaluated abrasion resistance of concrete as a function of finishing and curing, and fly ash inclusion. The concrete cured at high temperature and low humidity exhibited decreased resistance to abrasion. As expected, proper curing improved the abrasion resistance of concrete. The authors reported that at equal strengths at the time of abrasion testing, concrete with fly ash is as resistant to abrasion as no-fly ash concrete. Langan et al. (17) studied compressive strength and durability of concrete containing substitute materials at 50% replacement level by weight of portland cement used. Seven fly ashes, together with a limestone as an inert filler material (silica flour), were used as replacement materials. The results revealed that the presence of fly ash at high levels of cement replacement increased the weight loss due to abrasion at all ages relative to the concrete without fly ash.

Naik et al. (18) determined abrasion resistance of fly ash concretes. Both Class C (20-50%) and Class F (40%) mixture were proportioned. A superplasticizer was added to the Class F mixture (40% cement replacement) in order to keep the water-to-cementitious materials ratio below 0.36. Test results of the investigation showed that the Class C fly ash concrete mixtures (20-50%) showed similar results. The 40% Class F fly ash concrete mixture indicated higher depth of wear relative to the Class C fly ash mixtures. Barrow et al. (19) investigated abrasion resistance of concrete containing both ASTM Class F and Class C fly ashes. The fly ashes were used to replace cement, by 25 or 50%, by volume. Curing conditions for test specimens included combinations of 10°C, 23.8°C, and 37.7°C temperatures with 50% and 100% relative humidities. The authors indicated that due to lack of proper curing, abrasion resistance of fly ash concretes was less than that for the concrete without fly ash.

Bilodeau and Malhotra (20) studied abrasion resistance of concrete incorporating high volumes of Class F fly ash. Superplasticized proportions for concrete mixtures were developed to contain 55 to 60% fly ash of total cementitious materials. Their test results showed poorer performance for fly ash concretes relative to the reference concrete containing no fly ash. Naik and Singh (21) investigated the effects of temperature and a Class F fly ash addition on concrete strength and abrasion resistance under simulated hot weather conditions. The results revealed that at 23°C the abrasion resistance increased with increasing fly ash content. But at higher temperatures (35-49°C), the abrasion resistance was adversely affected by inclusion of the low-calcium fly ash. Ukita et al. (22) evaluated abrasion resistance of concrete incorporating a low-calcium fly ash in the range of 0-35% of cement by volume. Test results indicated that at a 15% cement replacement with fly ash, the abrasion resistance increased with the fineness of fly ash. However, at the fly ash content of 30%, the abrasion resistance of concrete was lower than that for the no-fly ash concrete.

Carette et al. (23) studied abrasion resistance of air entrained superplasticized high-volume Class F fly ash concrete. The amount of fly ash ranged from 55 to 60% of the total cementitious materials. The authors indicated that some concretes exhibited significantly lower abrasion resistance than other concretes of similar or even lower compressive strength.

MATERIALS AND TEST PROCEDURES

Materials

Type I portland cement was used; properties are shown in Table 1.

Fly Ash--A high-calcium (ASTM Class C) fly ash obtained from one source was used in this investigation. Chemical and physical properties of the fly ash were determined according to ASTM C 618 (Table 1).

Fine Aggregates--A natural sand with a 6.35 mm maximum size was used as a fine aggregate. This aggregate met the ASTM C33 gradation requirements. The physical properties of the fine aggregate are given in Table 2.

Coarse Aggregates--A coarse aggregate used in this study was 25.4 mm. nominal maximum size crushed limestone, and met the ASTM C33 gradation requirements. The physical properties of the coarse aggregate are given in Table 2.

Chemical Admixtures--A commercially available melamine-based superplasticizer was used. A resin-type air entraining admixture was used in all the mixtures.

MIXTURE PROPORTIONS

A total of eleven different mixtures were produced. Three of them were control mixtures, and the other eight mixtures contained ASTM Class C fly ash. Mixtures with fly ash were proportioned on the basis of using 1.25 parts of fly ash by weight for each part of portland cement by weight replaced. The proportions of Portland cement replaced ranged from 15 to 70%. The mixture proportions are given in Table 4. The control mixture without fly ash was proportioned to have the 28-day compressive strength of 41 MPa. The water-to-cementitious materials ratio [w/(c+f)] was maintained at 0.35 ± 0.02 and air content was kept at 6 ± 1% for the primary mixtures. The mixtures which did not meet the target water-to-cementitious materials ratio and/or air content requirements were classified as secondary mixtures. The primary mixtures only were used for data analysis and to derive the main conclusions from this study. The secondary mixtures were only used to evaluate the effect of air content on concrete strength and abrasion resistance. Production scale concrete batches of 0.76 m^3 each were mixed in a power-driven revolving-paddle mixer in accordance with ASTM C 192 at a precast concrete plant.

CASTING AND CURING OF TEST SPECIMENS

Slab specimens (305 x 305 x 102 mm) were cast for abrasion resistance determinations, and compressive strength test cylinders (152 x 305 mm) were cast according to ASTM C 192. The abrasion test specimens were cast using an internal and external vibrator. After casting, all test specimens were finished with a steel trowel. Immediately after finishing, the specimens were covered with plastic to minimize their moisture loss. All the test specimens were stored at temperatures of about 21°C in the casting room area of the precast concrete plant. They were demolded after 24 hours. They were then put into a moist curing room at 23°C temperature with 100 percent relative humidity until the time of test. The 70% fly ash mixture specimens were demolded after 11 days of curing under the casting room conditions (21°C) due to slow setting.

FRESH CONCRETE PROPERTIES

Fresh concrete properties such as slump, unit weight, temperature, and air content were determined according to applicable ASTM test methods. The results are presented in Table 3.

HARDENED CONCRETE PROPERTIES

Compressive strength of test cylinder, after capping with sulfur compound were tested for compressive strength according to ASTM C 39 test method. Test results are reported in Table 4.

The abrasion resistance tests were performed at 28, 91, and 365 days. The tests were conducted on the molded surface of the slab to get uniform finish surface for the test specimens. All specimens were tested at dry condition by the ASTM C 944 test method. Three separate test areas were tested on the same face of the specimen. The rotating cutter consisted of 24 grinding dressing wheels. The rotating cutter having washers with a diameter equal to that of the dressing wheels, produced depth of abrasion about 1 mm after about 60 minutes of exposure to the abrasive force. This was considered too slow. Therefore, it was decided to develop an accelerated technique, especially for concrete having high resistance to abrasion similar to one used in this study. This revised method was equipped with washers having smaller diameter relative to the dressing wheels. Furthermore, an amount (approximately one teaspoon) of silica sand ("Ottawa Sand" max. size 0.8 mm) was added to the concrete surface during exposure to abrasion at one minute intervals. At each wear location (circle of wear), for each wear time, three readings were taken at two points in the circle; and, the average of these six readings were recorded as one data point for each wear circle at the measured time of wear, Tables 5, 6, and 7.

TEST RESULTS AND DISCUSSIONS

The compressive strengths were measured at the ages of 1, 3, 7, 28, 91, and 365 days. Compressive strengths of primary mixtures are shown in Fig. 1 and 2. As anticipated, compressive strength test results show that the 1-day compressive strength of fly ash mixtures were substantially lower compared to the reference mixture (Mix No. C-3); it decreased with increasing fly ash content, probably primarily because sufficient cementitious action of the Class C fly ash was not yet activated.

The 3-day test results for up to 30 percent cement replacement (Mix No. P4-6 and P4-2) were comparable to the no-fly ash concrete (Mix No. C-3). However, a substantial decrease in the 3-day strength was observed when fly ash content was increased to replace 40% cement or higher. The 3-day compressive strength for the 70% fly ash mixture (Mix P4-8) was not determined because the concrete specimens were "soft". Similar trends were also observed at the 7-day age.

The 28-day peak strength was obtained for the 30 percent fly ash replacement concrete (Mix No.P4-2). Beyond the 30% cement replacement, the compressive strength of concrete decreased with increasing amounts of fly ash up to 70% cement replacement at the 28-day age. The 40 and

50% fly ash mixtures, however, attained the 28-day strengths in excess of 31 MPa, well suited for many structural uses.

The 91-day peak strength was also obtained for the 30 percent fly ash replacement concrete. The 40 percent fly ash mixture attained slightly lower strength compared to the no-fly ash concrete at this age. The 91-day strengths for both 50 and 70 percent fly ash concrete mixtures were 40 and 33 MPa, respectively, which are quite suitable for most structural uses. The strength results of the mixtures at 365 days followed the similar trend as that observed at 91 days.

As expected, compressive strength of concrete decreased as air content increased, especially above the 7-day age (Table 4). However, for the lower strength 70% fly ash mixture the effect of increased air content was negligible within experimental range (Fig. 3).

All concrete mixtures tested in this investigation showed excellent abrasion resistance, when tested in accordance with ASTM C 944. Their depth of abrasion remained less than 1 mm.

In order to determine relative abrasion resistance for all the concrete mixtures, the modified method established for this work was utilized (21). The test was stopped at 60 minutes or 3 mm wear, whichever occurred first. The abrasion tests were performed at the ages of 28, 91, and 365 days. The average depth of wear for test specimens for all the mixtures are presented in Tables 5 through 7.

Fig. 4 to 7 present the abrasion resistance for the six primary mixtures. In general abrasion wear decreased (i.e., abrasion resistance increased) with increasing age. Test results show that concrete mixtures up to 30 percent cement replacement by fly ash had abrasion resistance similar to that for the no-fly ash concrete. Beyond 30% cement replacement, it decreased slightly up to

50 percent cement replacement. The 70% Class C fly ash mixture exhibited the lowest abrasion resistance of all the mixtures tested in this work, primarily because of its lower compressive strength.

All the abrasion test results showed that the compressive strength was an important factor affecting abrasion resistance of concrete mixtures. Fig. 8 shows that depth of wear decreased linearly as compressive strength increased, without regard to the fly ash content.

The effect of air content on abrasion resistance of concretes is depicted in Fig. 9. The results show that variation in air content did not have any appreciable effect on the abrasion resistance of the concretes within the tested range.

CONCLUSIONS

1. Compressive strength of fly ash concrete containing up to 50% cement replacement was very acceptable for most structural applications.
2. Compressive strength of concrete decreased with increasing air content, except for the 70% fly ash concrete.
3. Abrasion resistance of concrete was strongly affected by its compressive strength, irrespective of fly ash content.
4. Fly ash concrete up to 30% cement replacement exhibited abrasion resistance similar to the concrete without fly ash, at the 28-day, 91-day, and 365-day ages.
5. Abrasion resistance of fly ash concrete with 40, 50 and 70 percent cement replacement was lower than the no-fly ash concrete.

6. Effect of air content on abrasion resistance of concrete was insignificant within the tested range.

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CONVERSION FACTORS

1 mm	=	0.0394 in.
1 MPa	=	145 Psi
1 kg/m^3	=	1.6855 lb/yd^3

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Table 1: Properties of Cement and Fly Ash Used

Chemical Composition	Cement, Percent	ASTM C 150, Type I	Fly Ash, Percent	ASTM C 618
Silicon Dioxide, SiO_2	20.2	-	30.5	-
Aluminum Oxide, Al_2O_3	4.7	-	17.2	-
Ferric Oxide, Fe_2O_3	0.3	-	5.5	-
Total, SiO_2 + Al_2O_3 + Fe_2O_3	25.2	-	53.2	50.0 Min.
Sulfur Trioxide, SO_3	+	3.0 Max.	+	5.0 Max.
Calcium Oxide, CaO	64.1	-	28.6	-
Magnesium Oxide, MgO	0.9	6.0 Max.	4.7	5.0 Max.
Titanium Dioxide, TiO_2	0.3	-	1.6	-
Potassium Oxide, K_2O	0.1	-	0.4	-
Sodium Oxide, Na_2O	0.1	-	2.0	1.5 Max.
Moisture Content	-	-	0.1	3.0 Max.
Loss on Ignition	-	3.0 Max.	0.3	6.0 Max.
Physical Properties of Cement				
Air Content (%)	7.1	12 Max.	-	-
Fineness (m^2/kg)	396	280 Min.	-	-
Autoclave Expansion (%)	0.03	0.8 Max.	-	-
Specific Gravity	3.16	-	-	-
Compressive Strength, MPa				
1-day	16.2	-	-	-
3-day	25.7	12.4 Min.	-	-
7-day	31.5	19.3 Min.	-	-
28-day	37.9	-	-	-
Vicat Time of Initial Set (min)	145	45 Min., 375 Max.	-	-
Physical Properties of Fly Ash				
Fineness Retained on No. 325 Sieve (%)	-	-	18.6	34 Max.
Pozzolanic Activity Index with Cement 28-day (% of control)	-	-	105	75 Min.
Water Requirement (% of Control)	-	-	90.4	105 Max.
Autoclave Expansion (%)	-	-	0.02	0.8 Max.
Specific Gravity	-	-	2.78	-

Note: + Data is not available

1 MPa = 145 Psi

Table 2: Physical Properties of Aggregates

Aggregates	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	SSD Absorption (%)	Dry Rodded Unit Weight (Kg/m^3)	Percent voids (%)	Fineness Modulus
Fine Aggregates	2.54	2.57	2.62	1.25	1765	30.5	2.66
Coarse Aggregates	2.76	2.78	2.84	1.07	1755	36.4	3.40

1 kg/m^3 = 0.0624 $lb/ft.^3$

Table 3: Mixture Proportions Using Pleasant Prairie Power Plant ASTM Class C (P-4) Fly Ash - 41 MPa Specified Strength*

Mixture Number	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3(P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
Cement (kg/m^3)	398	397	375	328	259	220	174	107	320	179	110
Fly Ash (kg/m^3)	0	0	0	72	139	182	216	310	71	226	316
Water (kg/m^3)	123	125	135	139	133	150	141	153	129	136	155
[w/(c+f)]	0.31	0.32	0.36	0.35	0.34	0.37	0.36	0.37	0.33	0.33	0.36
Sand, SSD (kg/m^3)	715	712	682	695	677	659	624	637	693	655	607
25 mm aggregates, SSD (kg/m^3)	1259	1264	1182	1207	1172	1153	1099	1128	1180	1139	1145
Slump (mm)	25	45	120	65	160	120	55	75	145	115	120
Air Content (%)	2.6	2.4	6.3	4.1	5.2	6.4	8.5	3.7	6.7	7	6.4
Superplasticizer (L/m^3)	2.7	2.7	2.9	2.9	2.8	2.7	2.6	2.6	2.8	2.7	2.6
Air Entraining Agent (ml/m^3)	280	330	270	300	350	515	810	905	420	885	1380
Air Temperature (°C)	20	20	21	21	21	21	26	26	-	-	-
Concrete Temperature (°C)	20	20	23	23	23	26	26	26	21	26	25
Fresh Concrete Density (kg/m^3)	2500	2500	2380	2445	2395	2360	2250	2335	2400	2335	2365
Hardened Concrete Density, SSD (kg/m^3)	2515	2510	2470	2510	2430	2415	2280	2300	2440	2340	2325

* Sub-designation P indicates primary mixtures and S indicates secondary mixtures.

1 kg/m^3 = 1.6855 lb/yd^3; 1 mm = 0.0394 in.; ml/m^3 = 0.026 U.S. fl $oz./yd^3$

L/m^3 = 25.9 U.S. fl oz/yd^3; $t_c = (t_f - 32)/1.8$.

Table 4: Compressive Strength Test Data - 41 MPa Specified Strength*

Mixture Number**	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-6(P)	P4-2(P)	P4-3(P)	P4-4(S)	P4-7(P)	P4-5(S)	P4-8(P)
Fly Ash, %	0	0	0	15	15	30	40	50	50	70	70
Air Content, %	2.6	2.4	6.3	4.1	6.7	5.2	6.4	8.5	7	3.7	6.4
Test Age, Days	Compressive Strength, MPa										
1	35.9	36.1	27.3	27.7	16.7	12.3	7.8	2.8	+	+	+
3	44.4	41.1	31.6	35.2	29.2	27.9	18.2	10.3	11.4	0.4	+
7	47.5	46.1	35.6	42.8	35.8	36.5	24.3	15.4	17.0	0.4	0.7
28	53.2	54.3	43.3	49.8	46.5	47.4	35.9	21.9	31.8	16.3	17.5
91	63.6	60.7	47.6	56.7	54.3	55.7	41.7	29.2	39.8	29.3	32.8
365	79.2	78.2	58.5	70.3	62.7	70.7	49.9	33.4	39.0	36.5	40.8

* The data presented are average of three observations.

** Sub-designation P indicates primary mixtures and S indicates secondary mixtures.

+ Did not measure - specimens were too soft to test.

1 MPa = 145 psi

Table 5: Abrasion Resistance Test Results Obtained by Using the Accelerated Test Method at 28-Day Age

Number*	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3(P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
sh, %	0	0	0	15	30	40	50	70	15	50	70
Minutes	Depth of Wear,mm										
5	0.11	0.10	0.23	0.14	0.14	0.18	0.34	0.44	0.18	0.23	0.30
0	0.26	0.26	0.46	0.36	0.34	0.49	0.57	1.00	0.32	0.63	0.68
5	0.64	0.41	0.69	0.52	0.50	0.78	0.90	1.38	0.54	0.92	1.29
0	1.04	0.63	0.82	0.70	0.66	1.00	1.09	1.71	0.64	1.11	1.40
5	1.17	0.75	1.01	0.92	0.85	1.27	1.38	1.90	0.90	1.27	1.89
0	1.45	0.88	1.11	1.08	1.02	1.58	1.63	2.34	1.03	1.49	2.00
5	1.65	1.04	1.28	1.24	1.18	1.77	1.86	2.63	1.18	1.58	2.35
0	1.88	1.21	1.39	1.39	1.33	2.01	2.04	2.94	1.33	2.16	2.81
5	1.99	1.33	1.57	1.62	1.50	2.18	2.22	-	1.49	2.34	3.04
0	2.17	1.50	1.75	1.78	1.74	2.28	2.44	-	1.65	2.56	-
5	2.28	1.67	1.89	1.96	1.88	2.45	2.62	-	1.80	2.72	-
0	2.42	1.85	2.06	2.16	2.05	2.56	2.76	3.68	1.95	2.85	3.55

* Sub-designation P indicates primary mixtures and S indicates secondary mixtures.

1 mm = 0.0394 in.

Table 6: Abrasion Resistance Test Results Obtained by Using the Accelerated Test Method at 91-Day Age

Number*	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3(P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
sh, %	0	0	0	15	30	40	50	70	15	50	70
Minutes	Depth of Wear,mm										
	0.08	0.08	0.14	0.06	0.05	0.08	0.20	0.22	0.1	0.22	0.34
0	0.23	0.23	0.29	0.26	0.17	0.29	0.46	0.48	0.27	0.57	0.61
5	0.43	0.45	0.49	0.41	0.35	0.54	0.74	0.74	0.53	0.88	0.96
0	0.55	0.62	0.75	0.62	0.53	0.78	0.96	0.90	0.64	1.10	1.25
5	0.72	0.75	0.96	0.79	0.76	1.01	1.18	1.15	0.82	1.50	1.51
0	0.94	0.90	1.10	0.94	0.90	1.18	1.37	1.39	0.99	1.65	1.68
5	1.13	1.03	1.24	1.11	1.04	1.29	1.55	1.64	1.10	1.77	1.89
0	1.27	1.12	1.39	1.27	1.18	1.50	1.74	1.85	1.26	2.01	2.03
5	1.37	1.27	1.46	1.44	1.31	1.71	1.92	2.04	1.39	2.16	2.16
0	1.50	1.41	1.58	1.53	1.48	1.85	2.04	2.24	1.50	2.27	2.32
5	1.64	1.50	1.68	1.65	1.64	1.97	2.21	2.38	1.59	2.33	2.47
0	1.80	1.63	1.77	1.75	1.70	2.08	2.34	2.54	1.71	2.41	2.59

* Sub-designation P indicates primary mixtures and S indicates secondary mixtures.

1 mm = 0.0394 in.

Table 7: Abrasion Resistance Test Results Obtained by Using the Accelerated Test Method at 365-Day Age

umber*	C-1(S)	C-2(S)	C-3(P)	P4-1(S)	P4-2(P)	P4-3(P)	P4-4(S)	P4-5(S)	P4-6(P)	P4-7(P)	P4-8(P)
ı, %	0	0	0	15	30	40	50	70	15	50	70
inutes	Depth of Wear, mm										
	0.07	0.08	0.14	0.11	0.18	0.23	0.41	0.28	0.11	0.24	0.47
	0.19	0.24	0.22	0.35	0.47	0.66	0.77	0.62	0.28	0.57	1.00
	0.28	0.35	0.18	0.48	0.46	0.90	0.98	0.90	0.41	0.85	1.33
	0.37	0.49	0.40	0.60	0.62	1.19	1.30	1.27	0.65	1.05	1.67
	0.42	0.63	0.57	0.81	0.73	1.42	1.51	1.52	0.85	1.27	1.87
	0.56	0.76	0.64	0.93	0.90	1.54	1.63	1.79	1.02	1.43	2.07
	0.71	0.85	0.73	1.11	1.03	1.78	1.77	2.09	1.18	1.61	2.40
	0.84	0.96	0.78	1.30	1.19	1.94	1.99	2.27	1.24	1.74	2.60
	1.08	1.04	1.04	1.57	1.22	2.05	2.15	2.46	1.35	1.94	2.74
	1.19	1.17	1.11	1.71	1.37	2.22	2.35	2.59	1.49	2.00	2.96
	1.17	1.28	1.26	1.84	1.49	2.50	2.56	2.76	1.67	2.30	3.07
	1.44	1.36	1.43	1.94	1.50	2.68	2.66	3.02	1.81	2.47	3.34

* Sub-designation P indicates primary mixtures and S indicates secondary mixtures.

1 mm = 0.0394 in.

LIST OF FIGURES