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An approach of using ideal gradating curve and coating paste thickness to design concrete performance-(2) Experimental work

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Abstract. The ideal gradating curve is used in this study to estimate densified aggregate blended ratio and total surface area of aggregate, there by under assigned paste amount of concrete, and coating paste thickness can then be deduced. Four groups of concrete mixtures were prepared and the corresponding concrete properties, such as workability, compression strength, ultrasonic velocity, surface resistivity and chloride ion penetration, were measured and finally the results are interpreted in terms of "coating thickness". The result shows as the coating thickness of the concrete is higher than critical one, the coating thickness on aggregate does affect the workability, and whatever workability is required the superplasticizer can be adjusted to achieve the demand workability. Under a fixed paste quality at the same age, coating paste thickness is inversely proportional to the concrete properties, especially as the coating thickness gets thinner.

Keywords: ideal gradating curve; coating paste thickness; concrete property; experimental work.

1. Introduction

In Taiwan, the Hwang's research group tried to achieve the maximum dry loose density by simply packing all solid particles including coarse aggregates, sand and fly ash, to reduce the quantity of lubricating paste but keep desired workability for HPC (Hwang 2008, Hwang *et al*. 2002) as well as RPM. As the category of material is less than three, the blend ration ($\alpha \cdot \beta$) (Lee *et al.* 2002, Chan *et al.* 2004) of solid materials ass the easily obtained by experimental work, otherwise the packing seems difficult especially as the material size finer than μm. Reactive powder mortar (RPM) is unique in attempting to optimize the entire grain size distribution of the composite matrix in order to reach maximum compaction (Chan *et al.* 2004, Lee *et al.* 2005).

Based on rational and complete theory deduction formulae in previous work, the ideal gradating curve was applied to achieve a dense packed concrete, and through a series of computation concrete mixture with an optimum coating paste thickness was obtained. Three conditions as fixed paste quality with excellent workability (EC-32), fixed paste quality with near zero slump (D-28) and (G-32) and various paste quality EC (A30), were studied and the corresponding fresh, hardening and

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Table 1 Chemical composition and physical property of material

Material		Cement	Fly ash	Slag
Chemical composition (*wt*.%)	SiO_2 (S)	22.0	51.2	34.9
	Al_2O_3 (A)	5.6	24.3	13.5
	Fe_2O_3 (F)	3.4	6.1	0.5
	S+A+F	31.0	81.8	48.6
	CaO (C)	62.8	6.3	41.8
	MgO (M)	2.6	1.6	7.2
	SO_3 (S)	2.1	0.6	1.7
	f-CaO	1.1	-	-
	TiO_2 (T)	0.5	-	-
	Na_2O (Na)	0.4	-	-
	K_2O (K)	0.8	-	-
	V_2O_5 (V)	0.1	-	-
	Loss on ignition (LOI)	0.51	4.85	0.31
	Insoluble residue	0.08	-	-
Potential clinker minerals	C_3S	40.10	-	-
	C_2S	32.80	-	-
	C_3A	8.9	-	-
	C_4AF	10.50	-	-
Physical properties	Fineness (cm^2/g)	2970	3110	4350
	Specific gravity (g/cm^3)	3.15	2.21	2.87
	Initial setting time (h:min)	4:37	-	-
	Final setting time (h:min)	8:22	-	-
	Retention on 325 sieve (%)	-	-	8.0

Properties	Type 1000 superplasticizer
Solid content (%)	42.99
Chloride ion content (ppm)	50.1
Insoluble residue (%)	0.15
Specific gravity (g/cm^3)	1.18
PH value	6.93

	Unit	Properties of aggregate						
Sieve #	-	3/8”	#4	#8	#16	#30	#50	#100
Sieve size	mm	9.5	4.75	2.36	1.18	0.59	0.297	0.145
Specific gravity SSD	g/cm^3	2.66	2.63	2.65	2.66	2.66	2.68	2.66
Specific gravity OD	g/cm^3	2.64	2.62	2.63	2.65	2.64	2.66	2.65
Absorption capacity (24 hr)	%	0.67	0.90	1.39	1.79	1.90	2.04	2.18
Unit weight	kg/m^3	1481	1427	1525	1513	1429	1373	1336

Note	
	• Type ordinary Portland cement: ASTM C150 • Class F fly ash (from Taiwan power), slag and aggregate : ASTM C33 • Type 1000 superplasticizer: ASTM C494

durability of concrete property were measured (Tsai 1997, Lo 2003). It proved that mixture design algorithm provided in this study is not only rapid, efficient but also guarantee to obtain desired concrete performance.

2. Experimental work

2.1 Material and mixture proportion

The basic material property in this study was shown in Tables 1-4 are the information for the natural gradating of EC-32 mixture, dense gradating of D-28 mixture, and gap gradating of G-32 mixture, respectively, under fixed paste quality but different aggregate content and packing density; while Table 5 was for EC (A30) with variable paste under fixed total amount of SP (A30) and water. Table 6 was the calculated coating paste thickness of corresponding mixture proportion in Table 2.

Table 2 Mixture proportion of EC-32 (w/b = 0.32)

		Mixture proportion (kg/m^3)				
	γ_s	EC-32-1.2	EC-32-1.4	EC-32-1.6	EC-32-1.8	EC-32-2.0
Coarse aggregate	2.64	766	720	674	628	581
Fine aggregate	2.64	988	929	869	810	750
Fly ash	2.18	161	151	141	132	122
Cement	3.15	318	388	459	529	599
Slag	2.88	16.7	20.4	24.1	27.9	31.6
Water	1.00	140	164	188	213	237
Superplasticizer	1.18	18.4	15.4	11.7	7.2	3.9

Table 3 Mixture proportion of D-28 (w/b = 0.28)

			Mixture proportion (kg/m^3)				
		GS	D-28-1.2	D-28-1.4	D-28-1.6	D-28-1.8	D-28-2.0
Aggregate	3/8"	2.64	644	619	595	571	547
	#4	2.62	185	178	171	164	157
	#8	2.63	388	373	359	344	330
	#16	2.65	293	282	271	260	249
	#30	2.64	192	185	178	170	163
	#50	2.66	223	215	207	198	190
Fly ash		2.18	204	196	188	181	173
Cement		3.15	201	252.7	305	357	409
Slag		2.88	10.6	13.3	16.0	18.8	21.5
Water		1.0	64.9	78.1	86.8	115.6	135.3
Superplasticizer		1.18	51.3	51.3	55.8	40.1	33.5

Table 4 Mixture proportion of G-32 (w/b = 0.32)

			Mixture proportion (kg/m^3)				
		GS	G-32-1.2	G-32-1.4	G-32-1.6	G-32-1.8	G-32-2.0
Aggregate	#4	2.62	1127	1079	1031	983	935
	#16	2.65	442	423	404	385	367
	#50	2.66	351	336	321	306	291
Fly ash		2.18	156	150	143	136	130
Cement		3.15	229	282	336	390	443
Slag		2.88	12.0	14.9	17.7	20.5	23.3
Water		1.0	88.6	111.2	140.5	162.8	184.0
Superplasticizer		1.18	38.4	31.7	18.3	12.0	6.7

Table 5 Mixture proportion of EC (A30)

		Mixture proportion (kg/m^3)		
	GS	EC (A30) 40160	EC (A30) 32160	EC (A30) 28160
Coarse aggregate	2.62	927	886	856
Fine aggregate	2.58	884	844	816
Fly ash	2.21	121	115	111
Cement	3.15	266	366	437
Slag	2.87	14.0	19.2	23.0
Water	1.0	155.0	148.0	143.4
Superplasticizer	-	5.0	12.0	16.6

2.2 Test items

The concrete was mixed according to ACI concrete practice (ACI Committee; Chang *et al.* 2001, Hwang 2009), and the corresponding properties of concrete were tested according to adequate ASTM standards, such as C143, slump; ASTM C31, C39 and C597, compressive strength at 3, 7, 28, 56 and 91 day age; C1202, chloride penetration; other standard as AASHTO was applied as well, such as ultrasonic pulse velocity (UPV), concrete resistivity (CR), etc (ASTM C 1202-97 1997).

3. Results and discussion

3.1 Fresh concrete property

Table 7 shows the fresh property of each concrete mixture, and from Fig. 1(a) and Fig. 2(a) it indicates that based on equal paste quality (w/b = 0.32) there exists an optimum coating paste thickness close to 25 μm for the best workability at both initial and 45-minutes; in Fig. 1(b) indicates as the aggregate is dense-packed and with equal low w/b as 0.28 the coating paste thickness should be increased to a threshold thickness, say 33.9 μm, to enhance the concrete

Table 6 Computational coating paste thickness of each mixture proportion

Mix		*w/b*	*n*	*Ksst*	$w_{partical}$	*S*	V_p	V_v	V_c	*t*	*w/c*
#	*Vv*	-	-	m^2/kg	kg/m^3	m^2/m^3	m^3/m^3	m^3/m^3	m^3/m^3	μm	-
(1)	(2)	(3)	(4)	(5)	(6)	(7) =(5)*(6)	(8)	(9)	(10) =(8)-(9)	(11) =(10)/(7)	(12)
EC-32	1.2	0.32	1.20	1.9944	1754.00	3498.16	0.339	0.289	0.050	14.3	0.473
	1.4		1.40		1649.00	3288.74	0.379		0.090	27.3	0.439
	1.6		1.60		1543.00	3077.34	0.419		0.130	42.1	0.413
	1.8		1.80		1438.00	2867.93	0.458		0.169	59.1	0.395
	2.0		2.00		1331.00	2654.53	0.498		0.209	78.7	0.382
D-28	1.2	0.28	1.20	1.3488	1924.66	2596.03	0.276	0.249	0.027	10.5	0.471
	1.4		1.40		1852.51	2498.72	0.303		0.054	21.7	0.426
	1.6		1.60		1780.37	2401.40	0.330		0.081	33.9	0.391
	1.8		1.80		1708.22	2304.09	0.357		0.109	47.1	0.389
	2.0		2.00		1636.07	2206.77	0.384		0.136	61.5	0.379
G-32	1.2	0.32	1.20	1.5044	1919.79	2888.16	0.274	0.243	0.031	10.7	0.485
	1.4		1.40		1837.91	2764.98	0.289		0.046	16.6	0.459
	1.6		1.60		1756.03	2641.80	0.304		0.061	23.1	0.450
	1.8		1.80		1674.15	2518.62	0.319		0.076	30.2	0.436
	2.0		2.00		1592.27	2395.44	0.334		0.091	38.0	0.424
EC (A30)	28.0	0.28	1.51	2.2713	1672.10	3797.87	0.357	0.261	0.096	25.3	0.348
	32.0	0.32	1.39		1730.10	3929.60	0.335		0.074	18.7	0.416
	40.0	0.40	1.23		1810.80	4112.90	0.304		0.043	10.4	0.572

Table 7 Fresh properties of concrete mixture proportion

Mix		*w/b*	*t*	*w/c*	Initial			45 min		
Designation	*Vv*	--	(μm)	--	Slump (mm)	Slump flow (mm)	Flow time (sec)	Slump (mm)	Slump flow (mm)	Flow time (sec)
EC-32	1.2	0.32	14.3	0.473	250.0	570.0	180	260.0	560.0	150
	1.4		27.3	0.439	270.0	710.0	150	280.0	725.0	120
	1.6		42.1	0.413	250.0	575.0	120	240.0	405.0	30
	1.8		59.1	0.395	240.0	420.0	10	180.0	300.0	5
	2.0		78.7	0.382	220.0	380.0	5	130.0	250.0	5
D-28	1.2	0.28	10.5	0.471	0.0	200.0	0	0.0	200.0	0
	1.4		21.7	0.426	0.0	200.0	0	0.0	200.0	0
	1.6		33.9	0.391	0.0	200.0	0	0.0	200.0	0
	1.8		47.1	0.389	250.0	570.0	320	230.0	530.0	270
	2.0		61.5	0.379	275.0	710.0	180	275.0	705.0	180
G-32	1.2	0.32	10.7	0.485	0.0	300.0	0	0.0	300.0	0
	1.4		16.6	0.459	175.0	395.0	150	185.0	400.0	180
	1.6		23.1	0.450	250.0	610.0	150	230.0	550.0	150
	1.8		30.2	0.436	255.0	600.0	150	185.0	450.0	30
	2.0		38.0	0.424	250.0	595.0	150	100.0	350.0	5
EC (A30)	28.0	0.28	25.3	0.348	285.0	700.0	55.0	280.0	680.0	60.0
	32.0	0.32	18.7	0.416	280.0	770.0	45.0	270.0	670.0	55.0
	40.0	0.40	10.4	0.572	270.0	670.0	45.0	200.0	310.0	20.0

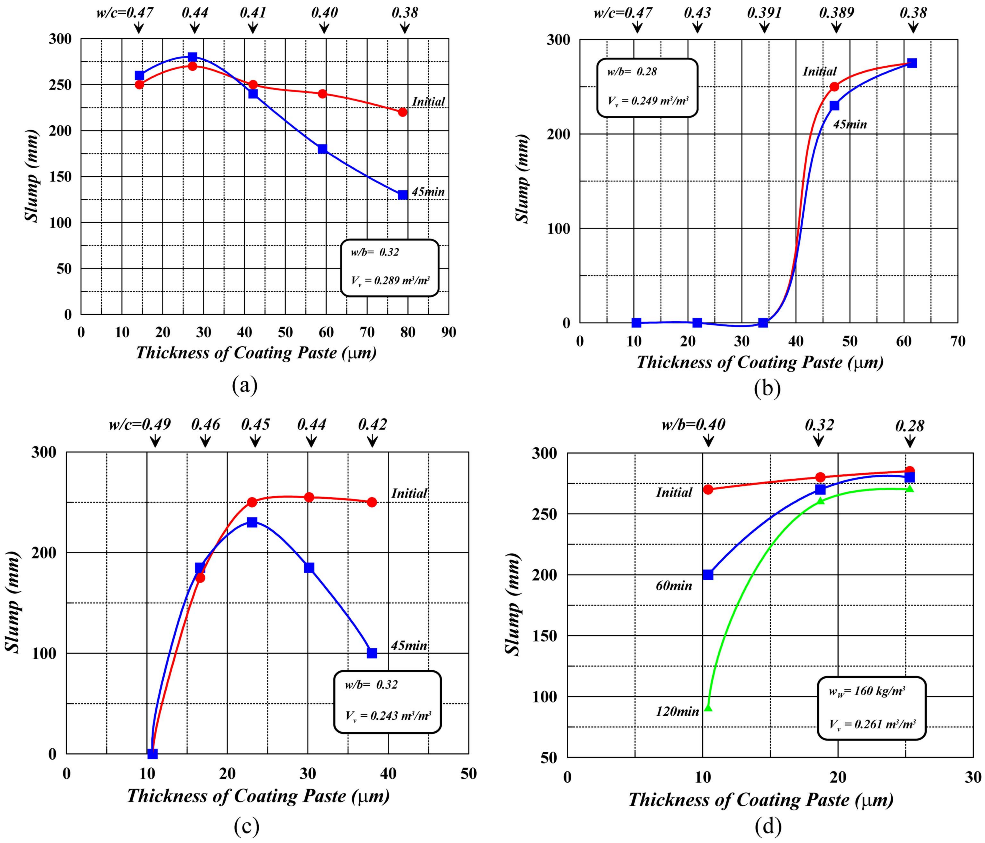

Fig. 1 The relationship of coating thickness vs. slump (a) EC-32, (b) D-28, (c) G-32 and (d) EC (A30)

workability from near zero slump to reach flowing concrete range where concrete slump greater than 250 mm as paste thickness greater than 47.1 μm and reach to a slump plateau as coating thickness reached 61.5 μm. This indicates that coating paste thickness for a dense packed system might increase friction force between particles but less climb energy for a particle to move around the particle, and hence below the threshold thickness the mixture will not be easy to move whereas the addition of SP will easily disperse the particle and flow away from each other easily to a flowing state (slump 250 mm, slump flow 600 ± 100 mm). Coating paste thickness increases from 47.1 μm to 61.5 μm (+30.5%), and SP dosage dropped from 40.1 kg/m^3 to 33.5 kg/m^3 (-16.3%), with a SP reduction rate of -0.455 kg/m^3 per μm thickness increment. Fig. 1(c) showed concrete with gap gradating the threshold thickness is 10 μm where near zero slump observed, the increment in coating thickness above will improve the workability to flowing concrete status at 23 μm thickness and might be worse after that point. It indicates that for gap gradating of concrete needs a sufficient coating to be worked with and after the addition of SP will enhance the workability to some stage of flowing concrete but after the optimum thickness the hydration of cement with lower *w/c* ratio tend to reduce the 45-minute slump. In Fig. 1(d), under fixed water content and paste content condition coating thickness increased from 10.4 μm to 25.3 μm (+143.3%) will cause the *w/b* ratio descends from 0.40 to 0.28, and slump loss tends to be worse as the decrement in paste quantity and reduction of the paste quality.

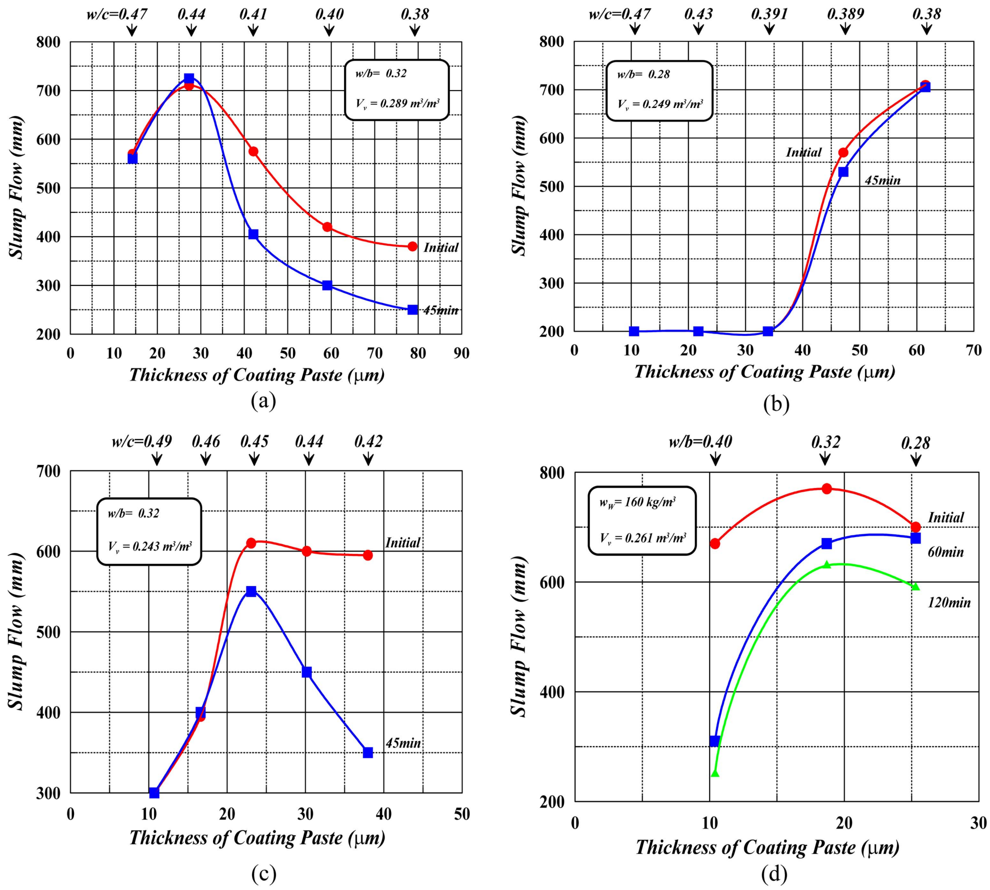

Fig. 2 The relationship of coating thickness vs. slump flow (a) EC-32, (b) D-28, (c) G-32 and (d) EC (A30)

3.2 Compression strength

Fig. 3 shows the thinner the coating paste thickness the less the initial strength due to the higher the *w/c* ratio. However the later-age strength will depend on the gradating of aggregate and paste quality of concrete mixture. Fig. 3(a) shows the higher the coating thickness the lower the 56-day and 91-day compressive strength. As the coating paste thickness is 14.3 μm, the compressive strength reached 70.1 MPa, whiles the coating paste thickness at 78.7 μm (+550%), the compressive strength reduced to 58.4 MPa (-16.7%). Due to the cement hydration and pozzolanic reaction the strength develops well and reached almost the highest value. For the dense packing and gap gradating situation, the strength will improve as the increment of coating thickness until the maximum strength reached where the pozzolanic reaction monitor the strength growth as shown in Figs. 3(b) and (c). Fig. 3(d) shows based on the minimum water content as 160 kg/m^3 as the coating paste thickness increases, the cement binder increases, the *w/b* ratio decreases, the quality is improved, and the compressive strength at all age increases.

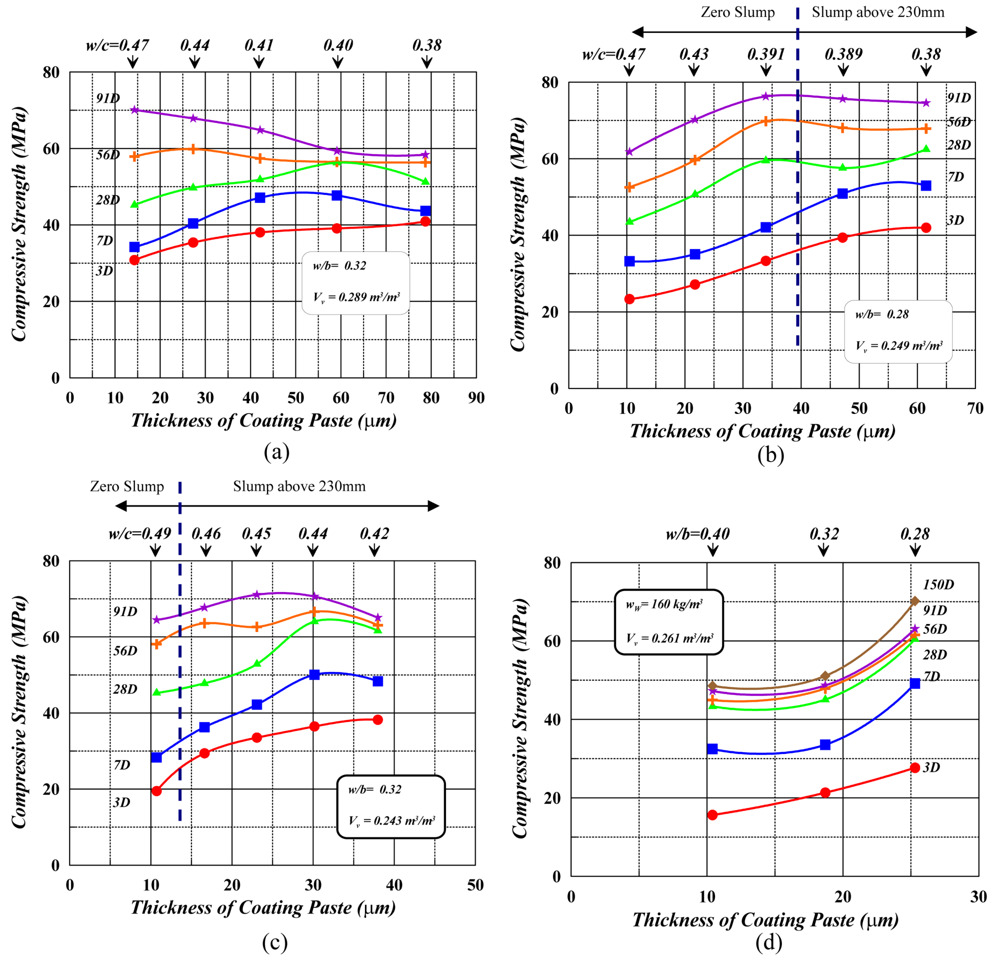

Fig. 3 The relationship of coating thickness vs. compressive strength (a) EC-32, (b) D-28, (c) G-32 and (d) EC (A30)

3.3 Ultrasonic pulse velocity (UPV)

Fig. 4(a) shows as the coating paste thickness increases the density of concrete decreases and hence the UPV decreases. Similar trend for UPV also is observed for the dense gradating and gap gradating as shown in Figs. 4(b) and (c) as the quality is fixed and there is no defect in concrete. This means that the less the paste in concrete the higher the UPV based on the same paste quality especially at long term age. As compared to the workability of concrete as shown in Fig. 1 it is clear that the quality of compaction will do affect the UPV at early age. In Fig. 4(d), it shows the UPV will increase as the reduction in *w/b* ratio, i.e., the increment of paste quality. As a conclusion, the UPV is linearly proportion to the density of concrete and the degree of compaction.

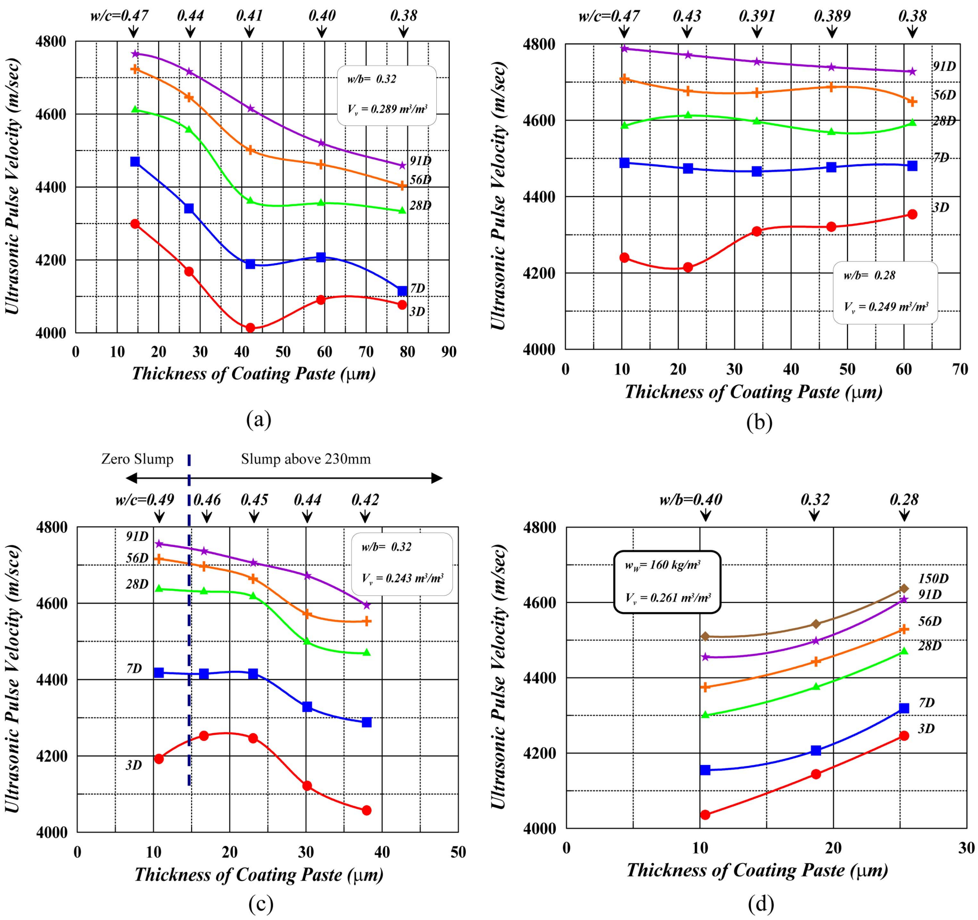

Fig. 4 The relationship of coating thickness vs. ultrasonic pulse velocity (a) EC-32, (b) D-28, (c) G-32 and (d) EC (A30)

3.4 Surface resistivity (SR)

SR is a matter related to the concrete durability since it is a degree of the obstruction of ion migration. As shown in Figs. 5(a) to (c) the thicker the coating paste thickness the lower the density and the lower the SR based on the equal quality of paste. And whatever gradating of aggregate is since the aggregate content of the concrete mixture design in this study is kept as high as possible the SR is always higher than 20 kΩ-cm at 91-day. Although at 3-day age and 7-day it is below 10 kΩ-cm; after 28 day age, that with low coating paste would have large SR. Fig. 5(d) shows the concrete under low water content as cement binder increase in consequence with good quality paste and high coating paste thickness will have high SR. This result also gives an important message that the low the water content the better the paste quality the higher the SR.

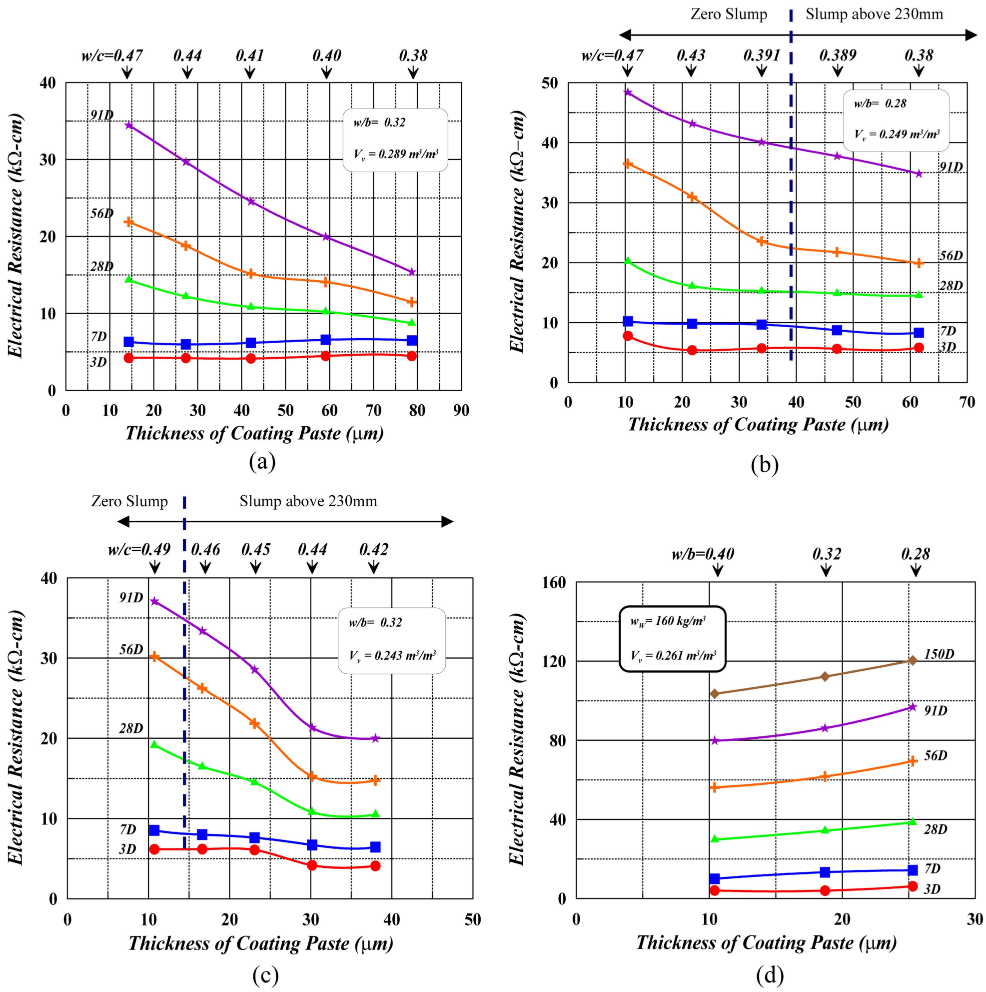

Fig. 5 The relationship of coating thickness vs. surface resistivity (a) EC-32, (b) D-28, (c) G-32 and (d) EC (A30)

3.5 Chloride ion penetration (CIP)

CIP is another measure for durability as SR and has good relationship with SR as $V = IR$. Figs. 6(a)~6(c) shows CIP current at 91-day and it indicates that the thicker the thickness the more the water content and the higher the CR current. The dense gradating of aggregate will make the concrete with much lower CIP current as shown in Fig. 6(b). Fig. 6(d) shows based on the same water content the thicker the thickness the lower the *w/b* ratio and then the lower the CIP current. From here it shows that the water content and the quality of paste affect directly on the CIP current.

3.6 The overall performance of concrete at 91 days

The long-term performance of concrete at 91-days has shown in Table 8. It is believed that at 91 day the hydration of cement is almost completed and the pozzolanic reaction has already started to

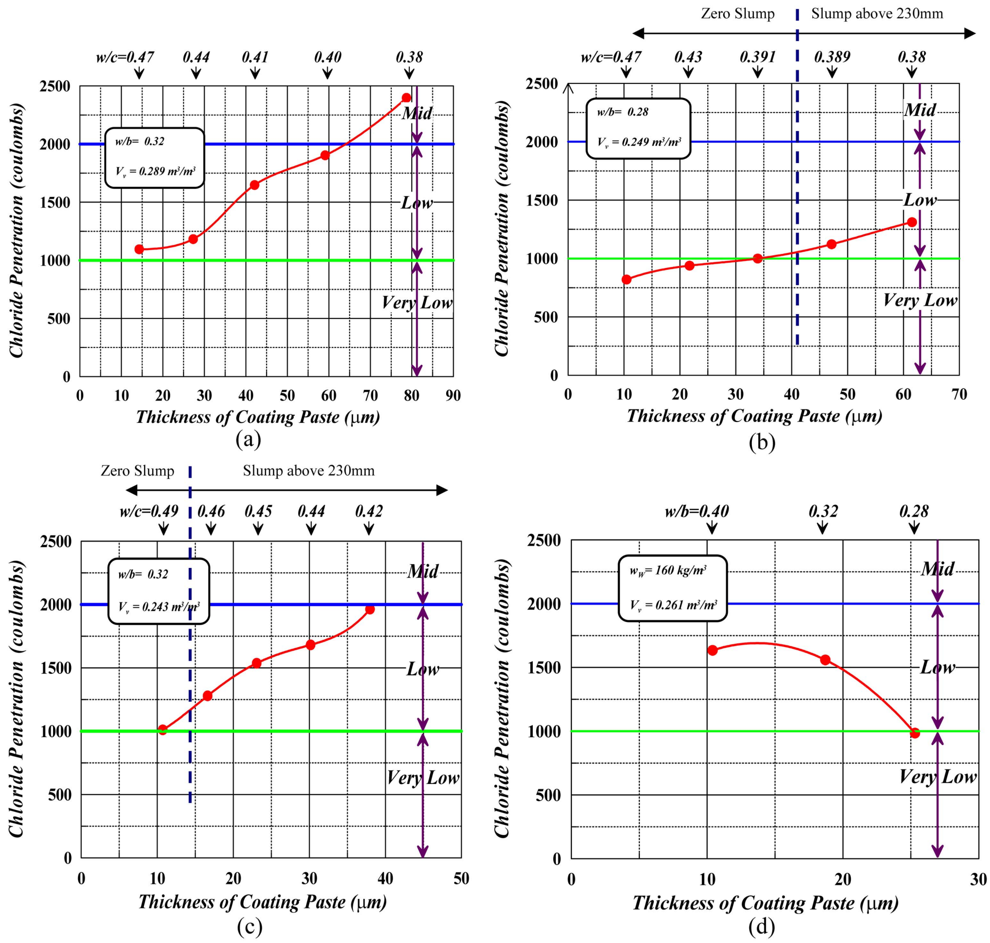

Fig. 6 The relationship of coating thickness vs. chloride ion penetration (a) EC-32, (b) D-28, (c) G-32 and (d) EC (A30)

some stage. The coating thickness and the property is inverse proportion.

3.6.1 Fixed paste quality

As shown in Table 8, for EC-32, D-28 and G-32 mixtures the property of concrete is inverse proportion to coating paste thickness with R^2 greater than 0.95. All data has indicated that the coating thickness is harmful to the property of concrete that is contrary to the tradition concept as the more the paste the better the property. The relation for compression strength, UPV, SR and CIP with unit coating thickness are -0.06 ~ -0.41 MPa/μm, -1.19 ~ -5.75 m/sec/μm, -0.25 ~ -0.81 KΩ-cm/μm and 694~723 coulomb/μm, respectively.

3.6.2 Fixed water content

Fig. 6(d) shows the higher the coating thickness the higher the property of concrete since the lower the *w/b* ratio. The relation for compression strength, UPV and SR with unit coating thickness are 0.17 MPa/μm, 10.05 m/sec/μm and 2.22 KΩ-cm/μm, respectively.

Table 8 The regression an equation of mixture system of (91 day)

Designation	t_{min} (μm)	t_{max} (μm)	Regression an equation	R^2	Else
EC-32	14.3	78.7	Compressive strength (MPa) = -0.197 × $t(\mu m)$ + 72.819	0.955	w/b = 0.32
	14.3	78.7	Ultrasonic pulse velocity (m/sec) = -5.001 × $t(\mu m)$ + 4836.645	0.984	
	14.3	78.7	Electrical resistance (kΩ-cm) = -0.296 × $t(\mu m)$ + 37.903	0.990	
	14.3	78.7	Chloride penetration (coulombs) = 20.823 × $t(\mu m)$ + 722.936	0.980	
D-28	33.9	61.52	Compressive strength (MPa) = -0.062 × $t(\mu m)$ + 78.454	0.984	w/b = 0.28
	10.5	61.52	Ultrasonic pulse velocity (m/sec) = -1.185 × $t(\mu m)$ + 4796.977	0.985	
	10.5	61.52	Electrical resistance (kΩ-cm) = -0.253 × $t(\mu m)$ + 49.673	0.960	
	33.9	61.52	Chloride penetration (coulombs) = 9.187 × $t(\mu m)$ + 717.385	0.979	
G-32	16.62	38.0	Compressive strength (MPa) = -0.410 × $t(\mu m)$ + 81.370	0.831	w/b = 0.32
	10.7	38.0	Ultrasonic pulse velocity (m/sec) = -5.753 × $t(\mu m)$ + 4829.017	0.951	
	10.7	30.2	Electrical resistance (kΩ-cm) = -0.807 × $t(\mu m)$ + 46.333	0.988	
	16.62	38.0	Chloride penetration (coulombs) = 33.767 × $t(\mu m)$ + 693.670	0.986	
EC (A30)	10.4	25.3	Compressive strength (MPa) = 79.174 – 4.749 × $t(\mu m)$ +0.174 × $t(\mu m)^2$	0.785	w_w = 160 kg/m^3
	10.4	25.3	Ultrasonic pulse velocity (m/sec) = 10.054 × $t(\mu m)$ + 4338.024	0.905	
	10.4	25.3	Electrical resistance (kΩ-cm) = 2.218 × $t(\mu m)$ + 44.910	0.918	
	10.4	25.3	-	-	

4. Conclusions

1. Existence of a critical coating paste thickness would impact concrete workability, when water/binder ratio increases, the critical thickness falls. If coating paste thickness is lower than critical value, the concrete is close to zero slumps, when coating paste thickness is higher than critical value, SP can still be used to reach high flowing state. Low paste thickness has high flowability, but excessive SP may aids better slump.

2. Under the same age and *w/b* ratio and fixed aggregate volume, for concrete with good workability, the compressive strength is inverse proportion to coating paste thickness.

3. Under fixed paste quality or same *w/b* ratio with the same aggregate blended ratio and the concrete has good workability, after 91 day, the ultrasonic passing velocity and surface resistivity are inverse proportion to coating paste thickness; while the chlorine ion penetration is linear proportion to coating paste thickness.

4. In terms of concrete workability, coating paste thickness should be greater than critical thickness; in terms of compressive strength, ultrasonic pulse velocity, surface resistivity, chlorine ion penetration, the thinner the coating paste thickness, the better the paste quality (low water/binder ratio) or the closer the aggregate contact each other.

5. Application of ideal gradating curve and theoretical estimation of coating paste thickness is proved to be a rapid approach for getting the optimum concrete mixture proportion.

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