Effect of Composition Variation and Particle Size of a Bristol Glaze

By Eung Keuk Lim

Department of Chemical Engineering, College of Engineering,

Seoul National University

브리스틀釉藥에 있어서의 組成과 粒度의 影響

林　　應　　極*

(1963. 4. 22 受理)

Abstract

A study was made of the effect of composition changes and particle size on appearance of raw bristol glazes fired at cones 5, 8, and 11. Alumina and silica, alkali and lime variations were made to get some of the more promising glazes determining maturing ranges, modulus of rupture, and other factors such as gloss, smoothness, opacity, eggshelling, crazing, pinholing and crawling for each glaze. Modulus of rupture was measured for the glazes fired at only cone 11.

要　約

브리스틀釉藥을 콘 5, 8, 11番으로 燒成됐을 때 나타나는 狀態에 對한 組成變化와 粒度의 影響을 硏究하여, 밝은 半艶消 또는 艶消釉藥을 얻을 수 있었다. 即 各釉藥에 對한 熟成範圍, 曲强度 및 光澤, 平滑性, 乳白度, Eggshelling, 龜裂, Pinholing, Crawling 等에 對한 因子를 決定하므로써 알미나, 珪酸, 알카리, 石灰를 變化시켜 實際 使用可能한 良好한 釉藥을 얻었다.

製造된 브리스틀釉藥은 最低 콘 5番부터 11番 또는 그 以上에서 긴 熟成範圍를 나타냈다. Crawling의 傾向에 있어서는 ZnO量이 增加될때 特히 甚했으나, $Al_2O_3 : SiO_2$의 比가 크고 ZnO 量이 많을때 乳白度가 顯著하였다. 釉藥의 粒子를 가늘게하면 熟成이 잘되나 微粒이면 Crawling이 커진다. 釉藥두께를 增加해도 Crawling 傾向이 커진다.

I. Introduction

The popularity of lead borosilicate glazes in the whiteware industry is due to the convenient maturing temperature, long maturing range, and good gloss. These advantages have been sufficient to outweigh some of the disadvantages of this type of glaze. The most outstanding of which are the presence of the poisonous lead and characteristic surface imperfections. Attempts to develop lead-less glazes have usually met difficulties from the aspects of both fusibility and glaze fit. The effect of the glaze application and its control has also been the subject of several investigations.

The bristol glaze has been extensively studied and described. The simplest and most systematic approach to the consideration of the composition of this type glaze seems to be by the way of eutectic relationships[1,2,3].

As already seen, fusibility is determined chiefly by the proper balance of fluxes, alumina and silica. The influence of additions of clay upon the fusibility has been largely discussed by Purdy[4] and Hill[5,6]. Harman and Swift[7] found that strontia increased the fusibility of the glazes and did

* 서울大學校 工科大學 化學工學科

not increase the expansion as much as baria. The use of lithium[8] has also been reported as beneficial to the strength of glazed ware in some cases. According to Hall[9] in comparison with calcia and zinc oxide, baria gives a lower elastic constant in all proportions used, but baryta is equivalent to the action of zinc oxide and less effective than the alkalies and calcia with respect to the influence on the coefficient of thermal expansion. McCutchen[10] observed that substitutions of strontia for other RO members in a glaze composition increased strength of the ware slightly. Thiess[11] observed that glazes high in feldspar and whiting reduced the strength of glazed ware considerably, whereas glazes high in flint and clay improved ware strength. Knecht[12] using a sanitary-ware glaze, found that increases of ZnO and flint at the expense of clay, feldspar and whiting resulted in decreased thermal expansion of the glaze. Silica in its amorphous or glassy state has an extremely low coefficient of thermal expansion. Since glazes are essentially glasses, the amount of silica in a glaze composition should decidedly affect the glaze fit and hence the resistance of the glaze to crazing. This result was noted by Thiess[11] and others. When, however, a glaze contains so much silica that will not enter into the glassy phase during firing, the excess will be present in the fired glaze as high expansion, and crystalline silica will promote poor glaze fit or even crazing in extreme cases.

The fineness of the glaze compositions is apparently also important. Koening and Henderson[13] noted that the compressive stress of a glaze increased with finer grinding of the glaze up to an optimum point and then decreased. Mellor[14] also noted that crazing tendencies were reduced with finer grinding of glazes. The literature on grinding and control of particle size in glaze slips has been reviewed by Parmelee[15]. There was also been considerable work on the measurement of consistancy of ceramic glaze slips[16], but little work has been done in correlating this property or other properties of the slip or of the fired glaze film with the measured particle-size distribution of the glaze slip. Various investigators have studied the relation of the extent of grinding to certain glaze defects[17], there are other references of interest on glaze preparation and application[18] and, specifically, on ball-mill grinding[19].

In this study a typical Bristol glaze composition was systematically varied both regarding RO constituency and alumina-silica contents. A typical glaze selected from composition variations of a Bristol glaze was used in the investigation on the effect of particle size. They were applied to a porcelain type body. The effect of composition variations and particle size on grinding time and application thickness on appearance for the glazes fired at cones 5, 8, and 11 was observed. In addition to appearance, mechanical strength of the glazed specimens fired at cone 11 was also measured. Maturing ranges were also determined by observation of appearance.

II. Procedure

A Bristol-type glaze selected for this investigation had the following molecular formula:

.30 KNaO　　　　　　　4.8 SiO_2
.35 ZnO　　.60 Al_2O_3　　.1 B_2O_3
.35 CaO

(1) Composition variation procedure

(A) Series 1 : Variation of Alumina-Silica Ratio: Using the constant RO constituency indicated in the base glaze formula, the alumina-silica contents were varied in Table IA, IB and IC.

(B) Series 2 : Variation of RO Constituency: Using the alumina-silica ratio from(Table I) that gave optimum strength results, the RO constituency was varied as follows.

(i) The CaO and ZnO were varied, keeping the KNaO constant. The former was decreased from 0.55 to 0.15 molecular equivalents, whereas the latter was increased from 0.15 to 0.55 molecular equivalents in steps of 0.2 equivalent each as shown in Table IIA.

(ii) The KNaO and CaO were varied keeping ZnO constant. The former was decreased from 0.4 to 0.1 molecular equivalents, whereas the latter was increased from 0.25 to 0.55 mole-

Table I and Table II

Molecular formula by composition
variations of a bristol glaze

	Glaze Code	KNaO	CaO	ZnO	Al₂O₃	SiO₂	B₂O₃
Table IA	1	.3	.35	.35	.4	2.0	.1
	2	.3	.35	.35	.4	2.8	.1
	3	.3	.35	.35	.4	3.6	.1
Table IB	4	.3	.35	.35	.4	4.4	.1
	5	.3	.35	.35	.5	2.5	.1
	6	.3	.35	.35	.5	3.5	.1
	7	.3	.35	.35	.5	4.5	.1
Table IC	8	.3	.35	.35	.5	5.5	.1
	9	.3	.35	.35	.6	3.0	.1
	10	.3	.35	.35	.6	4.2	.1
	11	.3	.35	.35	.6	5.4	.1
	12	.3	.35	.35	.6	6.6	.1
Table IIA	13	.3	.55	.15	.6	5.4	.1
	14	.3	.35	.35	.6	5.4	.1
	15	.3	.15	.55	.6	5.4	.1
	16	.3	.15	.55	.6	3.0	.1
Table IIB	17	.4	.25	.35	.6	5.4	.1
	18	.3	.35	.35	.6	5.4	.1
	19	.2	.45	.35	.6	5.4	.1
	20	.1	.55	.35	.6	5.4	.1

cular equivalents in steps of 0.1 equivalent as
shown in Table IIB.

(2) Body preparation

The body selected for this investigation had
the following porcelain-type body compositions.
Feldspar, 30%; ball clay, 30%; kaolin, 20%; and
flint, 20%. Chemical analyses of these raw mate-
rials are shown in Table III.

Table III Chemical analyses of raw materials

	Feldspar	Ball Clay	Kaolin	Flint
SiO₂	66.5	51.7	45.3	99.5
Al₂O₃	18.5	31.2	37.3	—
Fe₂O₃	.08	1.17	.61	—
TiO₂	—	1.7	1.5	—
CaO	.3	.2	.3	—
MgO	Tr.	.5	.2	—
K₂O	11.8	.36	.1	—
Na₂O	2.5	.58	.35	—
Ign. Loss	—	12.1	13.4	—
Total	99.68	99.51	99.06	99.5

Body specimens 3/4 in. diameter and $5\frac{1}{2}$
in. long were prepared by dry mixing and
vacuum extrusion.

(3) Glaze preparation and application

All glaze batches were calculated on the basis
of the actual chemical analyses of raw materials.

All glaze batches were ball-milled wet for six
hours. The specific gravities of all glazes were
adjusted to yield an application thickness of 5 to
7 mils when body specimens were dipped in
a controlled manner.

Glazes prepared for the alumina-silica and RO
variation series were applied to bar specimens.

All glaze batches and glazes on grinding time
and the glaze application thickness were contro-
lled in a same manner as the case of composi-
tion variations.

(4) Firing of glazes

All glazed specimens were fired in an electric
Globar kiln using a standard heating rate and
soaking period at cones 5, 8, and 11. Eight
specimens of each glaze body combination plus
unglazed specimens were included in each firing.

(5) Glaze evaluation methods

A standard system was employed in comparing
all glazes. A numerical grading method involving
gloss, smoothness, opacity, crazing, eggshelling,
crawling (Table IV). On the basis of these
ratings, fired specimens were classified by ap-
pearance into three catagories: (1) good appear-
ance, (2) fair appearance, (3) poor appearance.

All specimens were evaluated within 24 hours
after removal from the kiln. Delayed crazing was
evaluated three weeks later. No glaze that exhi-
bited crazing, either as removed from the kiln
or after storage, or appreciable pinholing or
crawling was considered as acceptable.

Transverse strengths for both glazed and un-
glazed bars were determined by means of an Olsen-
Boyd mechanical testing machine, and the results
were used as the criterion of glaze fit. An arbi-

Table IV Evaluation system for glaze appearance

Gloss		Smoothness		Opacity		Crazing		Eggshelling		Crawling	
Excellent	(G1)	Excellent	(S1)	High Opacity	(T4)	None	(Z1)	None	(E1)	None	(C1)
Good	(G2)	Good	(S2)	Moderate Opacity (T3)		Slight	(Z2)	Slight	(E2)	Slight	(C2)
Fair	(G3)	Fair	(S3)	Slight Opacity	(T2)	Moderate	(Z3)	Moderate	(E3)	Moderate	(C3)
Poor	(G4)	Poor	(S4)	Transparent	(T1)	Severe	(Z4)	Severe	(E4)	Severe	(C4)

trary rating of glaze fit was used in glaze evaluations as follows:

1) Good glaze fit: Transverse stregth of unglazed body increased.

2) Fair glaze fit: Transverse strength of unglazed reduced 20% or less.

3) Poor glaze fit: Transverse strength of unglazed body reduced more than 50%.

III. Results and Discussion

(1) Series 1: Alumina-Silica variation

The transverse strength results at cone 11 for the various glazes in this series are shown in Fig. 1.

The strength of the unglazed body was 10,600 lb. per sq. in. at cone 11. Glazes having an alumina-silica ratio of 1:5 were found to be semimat. Glazes having an alumina-silica ratio of 1:9 and 1:11 were found to be crazed moderately and extremely at cone 5. However glazes (7) and (8) having the same ratio and 0.5 equivalent alumina have satisfactory appearance and shown slight and moderate eggshelling. Glazes fired both cone 5 and cone 8 generally have shown slight and moderate eggshelling. The semimat and crazing noticeable both regarding strength and appearance were no doubt caused by the presence of silica in lack of that which could be taken into solution at the lower firing temperature than cone 11. Glaze (9) having an alumina-silica ratio of 1:5 did have satisfactory appearance and fair glaze fit and was an exception. Glazes having an 0.4 equivalent alumina increased the transverse strength as the alumina-silica ratio increased. But its strength did not reach to the unglazed body strength. It showed that they generally were

found to be poor glaze fit. All other glazes in this series were acceptable in appearance, and no outstanding differences in their effects on transverse strength at cone 11 were noted.

On the basis of these results, an alumina-silica ratio of 1:9 with 0.5 and 0.6 equivalent of alumina were selected as representing the optimum.

(2) Series 2: Variation in RO constituency

(i) The ZnO was varied from 0.15 to 0.55 molecular equivalents in steps of 0.2 equivalent at the expense of CaO, using the optimum alumina content and the optimum silica content selected from Table I. None of the RO variations used in this investigation significantly altered the transverse strength or appearance of glazed specimens as compared with Series 1.

Glazes of this series increased the opacity with increasing ZnO content up to 0.55 equivalent when fired at cones 8 and 11, but these results were reversely changed when fired at cone five. In addition, they were crazed severely and eggshelled moderately. Glaze (16) showed improperly low transverse strength as compared with any other glazes, but opacified the highest among them. It would appear that the excessive addition of ZnO to a glaze acted as a refractory and imparts whiteness. It wotld be one reason that glazes having the alumina-silica ratio of 1:5 had been found to be semimat at previous results. The ZnO content necessary to produce opacity, in general becomes less as the alumina and alkaline bases increased. A definite tendency toward crazing was observed at cone five and the alumina-silica ratio of 1:5. The transverse strength was increased by increasing the ZnO content at the expense of CaO, but an increase of ZnO decreased the fusibility at cone 11. It is well known that
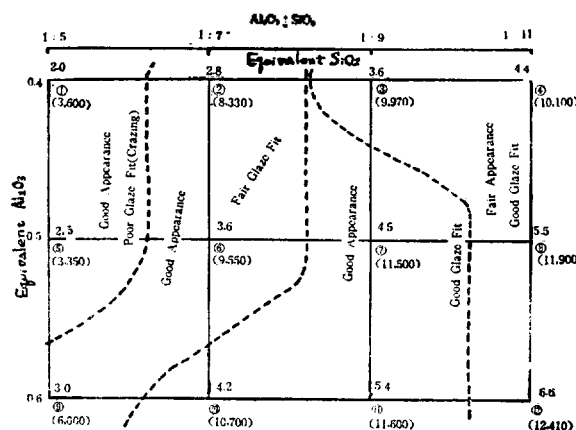
Fig. 1 Effect on transverse strength of varing Al₂O₃ and SiO₂ in a Bristol glaze(porcelain type body). Values in parentheses are transverse strength in lb/in².

the CaO reacts with both clay and flint and that ZnO reacts with flint. The CaO is the only component of a Bristol glaze that reacts readily with

clay to from fusible mixture.

(ii) The CaO was varied from 0.25 to 0.55 molecular equivalent in steps of 0.1 equivalent at the expense of KNaO, using optimum alumina and silica contents selected from Table I.

The alkali content decreased the modulus of rupture as compared with the action of the other bases commonly used, though it increased the fluidity of the molten glaze. There is an increase in glassy, transparent fusion, and a tendency to craze at cone 5 with increase in the amount of alkalies. It may be assumed that the glassy phase begins with the melting of the alkaline-alumina-silicates accelerated by the presence of calcium oxide. If a leadless glaze is to maintain good fit, the alkali content should not be above 0.3 molecular equivalent. The CaO content more than 0.45 molecular equivalent yielded glazes of fine crystalline mat texture at cone 5 or lower firing as shown by Danielson and Gordon[20]. In this case the refractoriness of the glaze is increased

Table V. Effect of composition variations of a Bristol glaze on appearance and modulus of rupture

Glaze No.	Cone 5-Gas Kiln	Cone 8-Gas Kiln	Cone 11-Gas Kiln	Cone 11 M of R. P. S. I.	Glaze Fit	Promixing at Cones
1	G3-S1-T1-Z2(Semimat)	G3-S1(Semimat)	G1-S1-T3-Z3-C2	3,600	−66	5, 8, 11
2	G1-S1-T3	G1-S1	G1-S1-T2	8,530	−19.5	5, 8, 11
3	G1-S1-E2-Z3	G1-S1-E2	G1-S1-T2-P2	9,970	− 5.94	8, 11
4	G1-S1-E2-Z4	G2-S1-E3-Z4	G1-S1-T2-P2	10,100	− 4.72	11
5	G4-S1-T1-Z2(Semimat)	G2-S1-Z3(Semimat)	G1-S1-T3-Z3-C2	3,350	−69.4	5, 8, 11
6	G1-S1-E2-T3	G1-S1-E2	G1-S1-T2	9,550	− 9.92	5, 8, 11
7	G1-S1-E2-T3	G1-S1-E2	G1-S1-T2	11,500	+ 8.49	5, 8, 11
8	G1-S1-E3	G1-S1-E3	G1-S1-T2-E2	11,900	+12.25	11
9	G2-T2-E2	G1-S1	G1-S1-T3	6,000	−43.4	8, 11
10	G2-T2-E3	G1-S1	G1-S1-T2	10,700	− 0.95	8, 11
11	G3-T3-E3-Z3	G1-S1-E2	G1-S1-T2	11,600	+ 9.45	8, 11
12	G3-T2-E3-Z4	G1-S1-E3	G1-S1-T2-E2	12,400	+17.0	8, 11
13	G2-T4-E3-Z4	G1-S1	G1-S1	10,900	+ 2.83	8, 11
14	G2-T3-E3-Z3	G1-S1-T2-E2	G1-S1-T2	11,100	− 4.72	8, 11
15	G2-T3-E3-Z4	G1-S1-T3-E3-Z2	G1-S1-T3	11,800	+11.31	11
16	G2-T2-E3-Z2	G1-S1-T4-E3	G1-S1-T4	3,960	−62.6	11
17	G1-S1-E2-Z4	G1-S1-E2-Z3	G1-S1-T2	9,460	−10.75	8, 11
18	G2-E3	G1-S1-E2	G1-S1-E2-T2	10,500	− 0.95	8, 11
19	G2-E3	G1-S1-E3	G1-S1-E2-T2	11,270	+ 6.32	11
20	G1-S1(Mat)	G2-S2-E4	G1-S1-E2-T2	11,980	+13.02	11

Transverse strength of the unglazed body is 10,600 P. S. I.
Glaze fit shows per cent change compared with unglazed body.

and devitrification with the separation of micro-crystalline structures was observed in glazes of widely different types. This is one of the most commonly used methods of forming the mat texture. The crystals have been identified as anorthite. The fusibility of this series was not effected by the variation of CaO content. An increase of CaO at the expense of KNaO increased the transverse strength at cone 11 and the degree of eggshelling increased gradually at cone 8.

(3) Series 3:

The results of the effect of grinding time and the glaze application thickness are shown in Table VI and Fig. II. An increase in grinding time up to 18 hours resulted in improved gloss and smoothness, less eggshelling and pinholing, less tendency to craze, and improved mechanical glaze fit except the glazes having 19-20 mils of thickness and grinding period of more than 6 hours which showed severe crawling.

Previous work has provided examples wherein finer grinding of glazes has resulted in improved appearance. Slight defferences in the distribution of particle size of the same glaze compositions in one instance were sufficient to make an important difference in the finished glazes. Investigators have also shown that finer milling has given better appearance and certain other benefits in

Table VI. Effect of particle size on grinding time and applicaation thickness of a Bristol glaze

Glaze Application Thickness(Mils)	Defects	Grinding Time				
		3 hrs.	6 hrs.	12 hrs.	18 hrs.	24 hrs.
2 — 3	Gloss	Good	Good	Good	Good	Good
	Eggshelling	Moderate	Slight	No	No	Slight
	Crawling	No	No	No	No	No
	Appearance Rating	B	A	A	A	A
	M of R	8,200	8,800	13,340	12,300	9,500
	Glaze Fit	—22.6	—17.0	+25.85	+16.0	—10.4
5 — 6	Gloss	Good	Good	Good	Good	Good
	Eggshelling	Slight	No	No	No	No
	Crawling	No	No	No	No	No
	Appearance Rating	A	A	A	A	A
	M of R	9,250	9,800	13,780	12,900	11,400
	Glaze Fit	—12.5	—7.6	+30.0	+21.7	+7.6
10—11	Gloss	Good	Good	Good	Good	Good
	Eggshelling	Slight	No	No	No	No
	Crawling	No	No	No	Slight	No
	Appearance Rating	A	A	A	A	A
	M of R	10,150	11,300	12,980	12,000	11,400
	Glaze Fit	—4.25	+6.6	+22.47	+13.2	+7.6
19—20	Gloss	Good	Good	Good	Good	Good
	Eggshelling	Slight	Slight	No	No	No
	Crawling	Slight	No	Bad	Bad	Bad
	Appearance Rating	A	A	C	C	C
	M of R	10,000	11,300	11,910	9,700	8,700
	Glaze Fit	—5.65	+6.6	+12.36	—8.5	—17.9

enamels, but there is also evidence in the litera-
ture of the dangers of overgrinding, which may
cause such defects as drying cracks, crawling and
wall splitting.

The microstructure became progressively better
with an increase in grinding time. The glazes
which were ground for 3 hours had a considerable
amount of undissolved matter, a rougher surface,
and more microdefects. With longer milling time,
there was less inhomogeneity and greater freedom
from microdefects.

The glaze fit was unimpaired by increasing
application thickness 5 to 11 mils, although the
reverse was true for a poor fitting glaze compa-
ring with the modulus of rupture. The modulus
of rupture developed in the glazes increased with
milling time up to 12 hrs., but decreased with
more than 12 hrs grinding time. Nevertherless
the glaze fit was not concerned with the glaze
application thickness of 5 to 11 mills.

On the basis of these results, a glaze application
thickness of 3 to 5 mils and 12 hrs grinding time
would normally be optimum.

IV. Summary

The results of this investigation concerning
glaze composition variation have revealed several
interesting facts. Whereas glaze fit depends on
the entire constituency of a glaze, the effect of
varying the amount of any individual oxide con-
stituent will depend on the relative degree of
glaze fit that the original glaze inherently pos-
sesses. Possibly the most significant result noted
for the study of the effect of glaze composition
variation on mechanical fit is that, whereas mec-
hanical strength is in general proportional to the
glaze stress condition, there is an optimum point
beyond which increases in glaze compression do
not further beneficiate mechanical strength of a
vitreous ware. It is thus also implied that there
is a wider choice of compositional variation when
the glaze compression is such that it is safely
within the range of optimum mechanical fit.

Opacity is increased as the zinc oxide is incre-
ased at the expense of the lime in all of the

Fig. II Effect on transverse strength of varing
grinding time and application thickness in a Bri-
stol glaze (porcelain type body). Values .in
parentheses are transverse strength (P. S. I).

series of Table IIA. Opacity is due to willemite
formation held in suspension, i. e.. not completely
taken into solution. The presence of the orthocl-
ase and the absence of the calcium silicates aid
indirectly in the development of opacity by their
effect upon the rate and extent of solution of
the willemite. It is plainly a case of supersatur-
ation under the time-temperature conditions of
the fusion, one of a compound separating out.
Whereas increase of silica in any of these mixtures
decreases opacity to some extent, the trials show
that the opacity is but very slightly affected
when increase in SiO_2 causes the formation of
wallastonite. There is a decided decrease in opa-
city, the decrease being directly proportional to
the increase in wallastonite as shown in Glaze
(15) and (16). The support of opacity seems to
be an additive function of the mineral norms
produced in the glaze.

All members of these series have excellent
gloss except cone 5 firing. The development of
gloss in these incompletely fused glazes seems to
be due to two factors of surface tension and
degree of fusion. Glazes fired above cone 5 have
been shown the excellent gloss with equal
equivalents of CaO and ZnO and other variations
of constitutions. The high surface tension of
these highly viscous glazes results, no doubt, in
a higher gloss than would otherwise be obtained.

With less viscous glazes, much more complete fusion would be required to obtain a gloss equal to that shown by many of the glazes in these experiments. The high gloss on all members is, no doubt, due to this high surface tension, which results from ultra-viscosity. This may explain why the influence of clay decreasing gloss did not show in the high zinc glazes as much as it did in the high lime glazes. The effect of additions of clay on gloss is not so pronounced in the case of the high feldspar glazes as in those with lower feldspar.

Crazing is due to shrinkage in volume and to surface tension. Strains certainly must arise from this drawing up of the glaze and these can find relief only in the cracking of the glaze. The shrinkage in volume of the mass due to changes in mineral constitution and the volume changes which these newly formed minerals pass through when cooling after having attained rigidity. We consider as being sufficient to account for all the strains necessary to produce crazing. A casual inspection that the craze lines extended through all depths of the glaze but closer inspection failed to disclose any break in their upper surfaces. The increased heat treatment should correct crazing on the upper surfaces of the glaze, and not at the lower surface is no doubt due to their high viscosity which materially decreases the rate at which reactions within the fusing glaze can take place.

With the maximum feldspar, high Al_2O_3 is required to overcome the finely rippled surfaces peculiar to egg shells. These egg shell surfaces are greatly like the surface produced by overfiring softer glazes, and since I find this egg shell finish increasing with increase heat treatment, it may be also said to be due to in this instance to overfiring, but I find this peculiar texture more characteristic of the high feldspar glazes which we know are not as fusible as the glazes of Table IA and IB of series 1 at cone 5.

The particle size in glaze compositions apparently had not significant effect on glaze fit. An increase in the time of grinding resulted in a tendency to crack after drying and in poor draining properties, which became progressibly worse with further reduction in particle size. Before adjusting the glazes with electrolyte, the viscosity and the amount of glaze taken up by a standard specimen increased with longer milling time. An increasing amount of electrolyte was required to adjust the glaze to similar feel with an increase in milling time. An increase in glaze grinding time to the optimum point results in improved gloss and smoothness, less eggshelling, pinholing, less tendency to craze and improved mechanical glaze fit. The excessive grinding of a glaze, however, may promote crawling.

Increasing the thickness of a glaze application exaggerates any crawling or crazing tendencies but increased the modulus of rupture. The optimum grinding treatment and application thickness should be determined and maintained for each glaze used commercially. Ware strength may be improved appreciably by use of a good fitting glaze. Failure to control glaze fineness and application procedures will result in ware of non-uniform quality.

Firing treatment, including such conditions as type of kiln, atmosphere, and rate of heating and cooling, period of soaking, and source of heat influence the character of glaze.

V. Conclusions

The following conclusions apply to the effect of glaze composition variations as herein investigated for Bristol glazes.

(1) Bristol glazes offer promise for the production of bright, semimat or mat glazes.

(2) Promising Bristol glazes may be produced to mature at least as low as cone 5 and up to cone 11 or possibly higher, and then tend to exhibit long maturing range.

(3) Bristol glazes exhibit a tendency to crawl, particularly with increasing ZnO content. High ZnO content is favorable to development of natural opacity in a Bristol glaze as is an increase in the $Al_2O_3 : SiO_2$ ratio.

(4) Increased fineness of Bristol glazes tends

to improve the maturing characteristics without significantly altering glaze fit, but excessive grinding of a glaze may promote crawling.

(5) Increasing the thickness of a glaze application exaggerates any crawling or crawling tendencies, but excessive thickness may promote crawling.

Bibliography

1) Watts, A.S., Bristol Glazes Compounded on a Eutectic Basis, *Trans. Am. Cer. Soc.*, 18, 631 (1916)

2) Watts, A.S., The Practical Application of Bristol Glazes Compounded on the Eutectic Basis., *ibid.*, 19, 301(1917)

3) Stull, R. T. and Howat, W. L., Deformation Temperatures of Some Porcelain Glazes., *ibid.*, 16, 454(1914)

4) Purdy, R. C., Stoneware Glazes, *ibid.*, 4, 61 (1902)

5) Hill, E. C., The Effect of Clay on the Fusibility of Bristol Glazes, *ibid.*, 18,508(1916)

6) Hill, E.C., Some Data on the Development of Terra Cotta Glazes, *J. Am. Cer. Soc.*, 3, 11—25(1920)

7) Harman, C.G. and Swift, H.R., Raw Leadless Whiteware Glazes, *ibid.*, 28, 48—52(1945)

8) Richardson, F.W., Use of Lithium Carbonate in Raw Alkaline Glazes, *ibid.*, 22, 50—53(1939)

9) Hall, F.P., Influence of the Chemical Composition on the Physical Properties of Glazes, *ibid.*, 13, 182(1930)

10) McCutchen, E.S., Strontia and its Properties in Glazes, *ibid.*, 27, 233—38(1944)

11) Thiess, L.E., Influence of Glaze Composition on Mechanical Strength of Electrical Porcelain, *ibid.*, 19, 70—73(1936)

12) Knecht, A.O., Control of Crazing in Sanitary-Ware Glazes by Mayer and Havas Coefficient of Expansion Factors, *ibid.*, 23, 61—63(1940)

13) Koenig, J.H. and Henderson F. C., Particle Size Distribution of Glazes, *ibid.*, 24, 286—97

(1941)

14) Mellor, J.W., Crazing and Peeling of Glazes, *Trans. Cer. Soc.*(Engl.), 34, 1—112(1935)

15) Parmelee, C.W., Recent Advances in Grinding Control of Particle Size in Glaze Slips, *Cer. Ind.*, 25, 48—50(1940)

16) a) Morgan, W.R. and McDevitt, W. B., Eliminating Glaze Defects by Consistency Control, *Bull. Am. Cer. Soc.*, 17, 443—44 (1938)

　b) Shearer, W.L., Control of Plasticities of Ceramic Slips, *J. Am. Cer. Soc.*, 15, 622—29(1932)

　c) Turnbull, E.D., Measuring Consistency of Glaze Slips., *Cer. Ind.*, 17, 116—117(1931)

　d) Spurrier, H., Notes on Terra Cotta Glaze Consistency, *J. Am. Cer. Soc.*, 12, 577—80 (1929)

　e) Tetterolf, L.D., Study of Consistencies of Raw Terra Cotta Glazes, *ibid.*, 13, 675—82 (1930)

17) a) Rancke, C., Cause of Defects and Their Cure, *Keram. Rundschau.*, 44, 37—38(1936)

　b) Berdel, E., Glaze Defects and Their Correction, *ibid.*, 45, 70—71. 96—98(1937)

18) a) Brown, L.H., Preparing Slips and Glazes for Best Results, *Cer. Ind.*, 22. 376—78(1934)

　b) Brown, L.H., Application of Glazes, *Bull. Am. Cer. Soc.*, 17, 441—42(1938)

　c) Schlenkermann, W., Grinding Time and Water Content of Glazes, *Keram Rundschau*, 42, 15—17(1934)

19) a) Coghill, W.H. and Devaney, E.D., Ball-Mill Grinding, *Bur. Mines Tech. Paper*, No. 581, 56pp (1937)

　b) Kleinfeldt. H.R., New Development in the Field of Pebble Mill Grinding, *Cer. Age*, 14, 214—17(1929)

20) Danielson, R.R. and Van Gordon, D. V., Leadless Opaque Glazes at cone 04, *J. Am. Cer. Soc.*, 33, 323—27(1950)