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A STUDY ON THE MECHANISM OF DRYING SHRINKAGE REDUCTION THROUGH THE USE OF AN ORGANIC SHRINKAGE REDUCING AGENT

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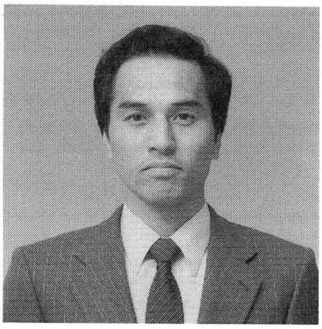

Rokuro TOMITA

SYNOPSIS

A large amount of research has indicated that drying shrinkage of cementitious materials is caused by compressive force resulting from surface tension of pore water. The author and his colleagues have developed a shrinkage reducing agent whose main ingredient consists of lower alcohol alkylene oxide adducts, a type of surfactant that reduces surface tension of pore water. This study was carried out to determine the most effective composition of this organic adduct. Shrinkage reduction mechanisms in hardened cement paste, mortar and concrete are also discussed. The results show that drying shrinkage in hardened cement can be reduced by decreasing surface tension.

Key words: Drying shrinkage, concrete, mortar, paste, surface tension, shrinkage reducing agent, alcohol alkylene oxide adducts

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1. INTRODUCTION

One strong theory regarding drying shrinkage of cementitious materials is that it is caused by compressive force resulting from surface tension of pore water. Based on the behavior of moisture in hardened cement paste, Chujo, et. al.[1], explain drying shrinkage of hardened cement paste as a result of capillary action on the remaining volatile moisture content. According to this theory, if an agent capable of lowering the surface tension of water in the hardened cement specimen is introduced, capillary action will be decreased and reduction of drying shrinkage will become possible. Sato, et. al.[2], used an organic shrinkage reducing agent from lower alcohol alkylene oxide adducts to prove this theory. However, despite the use of various agents, they were unable to extend their proof of this theory to include concrete.

For this paper, a lower alcohol, alkylene oxide and one of their components, lower alcohol alkylene oxide adducts, were used to reduce the surface tension of water in a hardened cement specimen; the relationship between surface tension and reduction of drying shrinkage was studied, and the mechanism of how these agents reduce drying shrinkage is explained. In addition, three types of shrinkage reducing agents were added to mortar and to concrete, and the mechanism of how they reduce drying shrinkage studied.

2. TESTS OF DRYING SHRINKAGE REDUCTION EFFECT FOR EACH ADDUCT

2.1 Butyl Alcohol Drying-shrinkage Test

(1) Reduction of surface tension

The liquid surface tension of normal butyl alcohol in solutions of various concentrations was measured with a Wilhelmi surface tension meter; the results were as shown in Fig. 1.

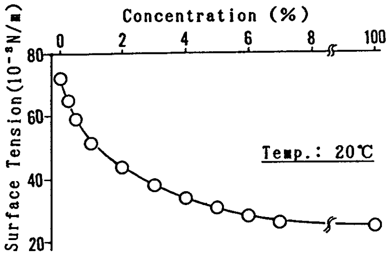

Fig. 1 Surface tension of normal butyl alcohol in solutions of various concentrations

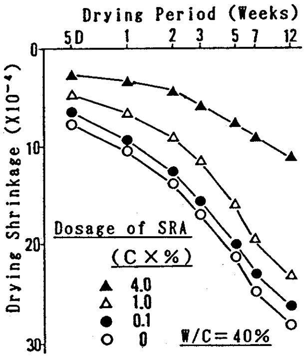

Fig. 2 Results of drying shrinkage tests using normal butyl alcohol

The surface tension for a 0.25% solution was about 10% lower than that for pure water and, as the strength of the solution is increased, the surface tension falls even further. At full strength (100%), the surface tension is only 33% that of pure water, or approximately 25 x 10^{-3} N/m. Further, surface tension is reduced rapidly at first for weak solutions but the reducing action then slows down (see Fig. 1), a behavior similar to that seen in surfactants.

(2) Reduction of drying shrinkage

Fig. 2 shows the results of drying shrinkage tests carried out using normal butyl alcohol in the amounts of 0.1, 1.0 and 4.0% by weight of cement (0.25, 2.5 and 10% of water content, respectively). Standard test methods were used, in which the specimen was cured in 20°C water after demolding and dried at 20°C, 60% relative humidity. Further, since all the shrinkage reducing agents used for these tests were in liquid form, they were used in place of the mixing water. Even when the extremely small amount of 0.1% was used, a reduction in drying shrinkage, albeit small, was observed. As the amount was increased, the reduction in drying shrinkage also increased; at the 4.0% level, the drying shrinkage ratio was 40%.

The relationship between the drying shrinkage ratio of the control paste and specific surface tension of pure water for pastes of various ages is shown in Fig. 3. The relationship between drying shrinkage ratio and specific surface tension is not 1:1, and drying shrinkage ratio increases as the drying period progresses. In other words, rate of reduction of drying shrinkage decreases as age increases, but the great influence of surface tension reduction on drying shrinkage can be seen.

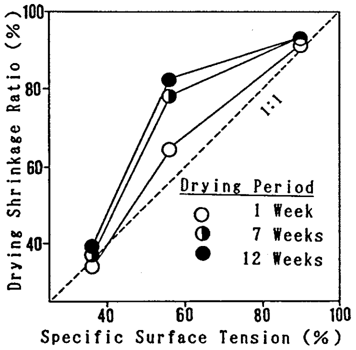

Fig. 3 Relationship between drying shrinkage ratio and specific surface tension

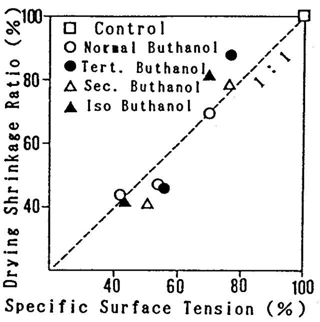

Fig. 4 Effect of specific surface tension on drying shrinkage for metamers of butyl alcohol

Similar tests were carried out using metamers of butyl alcohol in the amounts of 1.0 and 5.0%. The relationship between specific surface tension and drying shrinkage ratio at 1 week is shown in Fig. 4. As shown in the figure, the relationship is 1:1, or a straight line. If the component used belongs to the same family, the surface tension of the mixing water provides a physical indicator on which to base an evaluation of drying shrinkage. However, it was shown that the drying shrinkage ratio increases in relation to specific surface tension as the drying period progresses.

2.2 Alkylene Oxide Drying Shrinkage Test

Table 1 shows the results of drying shrinkage tests in which glycols, similar in composition to butyl alcohol, and alkylene oxide were added to the paste in the amount of 4% by weight of cement. Since alkylene oxide caused foaming in cement paste, a defoaming agent was also added. When 4% ethylene oxide or propylene oxide, with their comparatively high molecular weights, were used, drying shrinkage was reduced by approximately one-half. However, low-molecular-weight glycols increased drying shrinkage, and only a slight effect was observed when tri-ethylene glycol was used.

Table 1 Drying shrinkage of paste containing alkylene oxide

No	Type of Shrinkage Reducing Agent	Drying Shrinkage Ratio (%)		
		1 week	4 weeks	12 weeks
①	Ethylene glycol (62)	174	182	172
②	Di-Ethylene glycol (106)	121	137	134
③	Tri-Ethylene glycol(150)	95	77	82
④	Ethylene Oxide* (600)	47	45	52
⑤	Ethylene Oxide* (1000)	36	38	50
⑥	Propylene Oxide* (400)	33	36	49

Number in parenthesis is average moleculer weight.
* Defoaming agent is co-used in case ④,⑤ and ⑥.

2.3 Alcohol Alkylene Oxide Adduct Drying Shrinkage Test

(1) Tests related to type of alcohol added

Two types of alkylene oxide, ethylene oxide and propylene oxide, were chosen and assumed to have an average polymerization of 3, and added to four types of alcohol having carbon numbers 1, 2, 3 and 4, to form alcohol alkylene oxide adducts. These eight types of alcohol alkylene oxide adducts, each in the amount of 2% by weight, were mixed with mortar. Results of drying shrinkage and compressive strength tests are shown in Fig. 5. The value for drying shrinkage is that for a drying period of 13 weeks, while that for compressive strength is for standard curing at four weeks. The results are compared with those for the control mortar, to which no alcohol alkylene oxide adducts were added.

A 30% reduction in drying shrinkage was observed with propylene oxide mixtures. For ethylene oxide the larger the carbon number of the alcohol added, the greater the shrinkage reducing effect and ethylene oxide with a carbon number of 4 (normal butylene alcohol) had an effect equivalent to that of propylene oxide mixtures. Thus, it may be seen that the type of alcohol added to the various types of alkylene oxide greatly influences drying shrinkage. In comparison to control figures, ethylene oxide mixtures showed compressive strength values of 90%, while propylene oxide mixtures showed values of 85% or higher, depending on the type of alcohol used.

(2) Propylene oxide adduct test

Propylene oxide with an average polymerization of 1-6, which showed overall good results, was mixed with 4 types of alcohol to form 21 types of alcohol alkylene oxide adducts for further testing, and tests similar to the above were carried out using mortar to which 2% of each of the 21 alcohol alkylene oxide adduct mixtures was added. The results are shown in Fig. 6. It was demonstrated that the greater the polymerization of propylene oxide, the greater the reduction in drying shrinkage. On the average, when polymerization was 4, the shrinkage reduction effect was the greatest. However, for a polymerization of 3 or more, there was no great difference in shrinkage reduction, with the ratio falling between 60 and 70%. It was also confirmed that mixtures providing the greatest reduction in drying shrinkage showed the lowest surface tension.

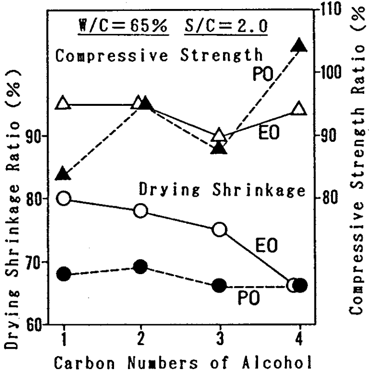

Fig. 5 Results of alcohol alkylene oxide adduct tests

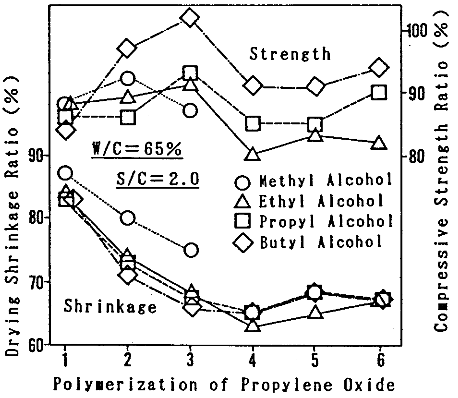

Fig. 6 Results of alcohol propylene oxide adduct tests

Addition of methyl alcohol resulted in little reduction of shrinkage; reduction of drying shrinkage by other types was roughly equal. Further since the compressive strength ratio of all types was 80% or higher, this would be an effective agent for practical application. As described above, reduction of drying shrinkage and effectiveness of alcohol alkylene oxide adducts were tested and evaluated on the basis of polymerization and type of alcohol added. If propylene oxide having a polymerization of 3 to 6 is used and the type of alcohol added is ethyl, propyl or butyl alcohol, an alcohol alkylene oxide adduct having a strong shrinkage reducing effect is formed.

3. MORTAR AND CONCRETE TESTS

3.1 Shrinkage Reducing Agents

Three types of alcohol alkylene oxide adducts, each having different structures and polymerization, were tested. Their main components are shown in Table 2. Shrinkage reducing agent A (SRA-A) is ethylene oxide to which methyl alcohol has been added. As this is a low-polymer compound, it is highly soluble in water. Based on the results obtained from tests described in Section 2, its effect on reduction of drying shrinkage is comparatively small and it causes a small amount of air entrainment. Shrinkage reducing agent B (SRA-B) is propylene oxide to which normal butyl alcohol has been added. As studied in Section 2, this compound is the most effective among its type in reducing drying shrinkage. Its water solubility is somewhat poor, and it has a weak defoaming effect.

Shrinkage reducing agent C (SRA-C) consists of ethylene oxide and propylene oxide in order of polymerization, to which normal butyl alcohol has been added. Test results show that its effect is similar to that of SRA-B in reducing drying shrinkage. The polymerization of its structural components is distributed over a wide area of secondary sources; it has an average molecular weight of 300, high in comparison to that of SRA-A and SRA-B. These materials have the same specific gravity as water. They do not show abnormal air entrainment and do not adversely affect the hydration of cement. Further, SRA-A and SRA-C have a long record of actual application and papers on their effectiveness in reducing drying shrinkage and cracking in concrete have been published [3], [4], [5].

Table 2 Chemical composition and physical properties of SRA

Abbre-viate Symbol	Chemical Composition*	Specific Gravity	Surface Tension (10^{-3}N/m)	Average Moleculer Weight
SRA-A	$CH_3\text{-}(C_2H_4O)_3\text{-}H$	0.98	38.9	150
SRA-B	$C_4H_9O\text{-}(C_3H_6O)_3\text{-}H$	0.99	29.1	250
SRA-C	$C_4H_9O\text{-}(C_2H_4O)_{2.5}$ $\text{-}(C_3H_6O)_2\text{-}H$	0.99	28.9	300

* These are the average compositions and their numbers of polymerization distribute widely.

3.2 Mortar Test Results and Discussion

(1) Type and amount of shrinkage reducing agent

The materials used to make mortar were ordinary portland cement, pure water (surface tension: approximately 72 x 10^{-3} N/m) and fine aggregate made from glass (specific gravity: 2.5; moisture absorption: 0%). The water-cement ratio (W/C) is 50% each and the cement-fine aggregate ratio (C/S) is 2.48. When the mortar was dried under conditions of 30% or 80% relative humidity, a hydrostatic liquid, a saturated solution of $CaCl_2 \cdot 6H_2O$ (32% relative humidity) and NH_4Cl (79% relative humidity), were used to control moisture. Table 3 shows the results of drying shrinkage tests for mortar after a drying period of 26 weeks. In the table, the results are compared with control figures.

Table 3 Results of drying shrinkage tests for mortar specimens

SRA		Relative Humidity at Drying						Surface Tension of Water (10^{-3}N/m)
Type	Dosage Ratio (CX%)	30% RH		60% RH		80% RH		
		M.D.S. (X10^{-4})	D.S.R. (%)	M.D.S. (X10^{-4})	D.S.R. (%)	M.D.S. (X10^{-4})	D.S.R. (%)	
Non	0	13.47	100	13.02	100	11.17	100	72.2
A	1	12.01	89.2	11.72	90.0	10.16	91.0	60.5
	2	11.75	87.2	10.58	81.3	9.61	86.0	57.3
	4	10.19	75.6	9.29	71.4	8.70	77.9	52.6
B	1	10.78	80.0	10.58	81.3	9.87	88.4	49.2
	2	9.16	68.0	9.06	69.6	8.99	80.5	45.4
	4	8.16	60.6	8.44	64.8	7.79	69.7	40.4
C	1	10.06	74.7	10.10	77.6	9.25	82.8	41.8
	2	9.37	69.6	9.29	71.4	8.57	76.7	37.0
	4	9.12	67.7	8.38	64.4	8.21	73.5	32.0

M.D.S. : Measured Value at 26 Weeks of Drying
D.S.R. : Drying Shrinkage Ratio Based on the Control Data

Average shrinkage ratios for various amounts of shrinkage reducing agent and humidity conditions are shown in Fig. 7. The reduction in drying shrinkage is clearly shown for each shrinkage reducing agent and the increase in amount used in each case. A comparison of the agents tested shows that SRA-A had the smallest effect. If the more effective SRA-B and SRA-C are compared, SRA-C had the greatest effect when small amounts were used, while SRA-B had the greatest effect when the amount used was 4%. Therefore it can be seen that the three types of shrinkage reducing agents had different characteristics, depending on the type.

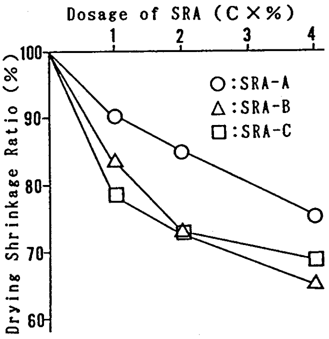

Fig. 7 Relationship between SRA dosage and drying shrinkage

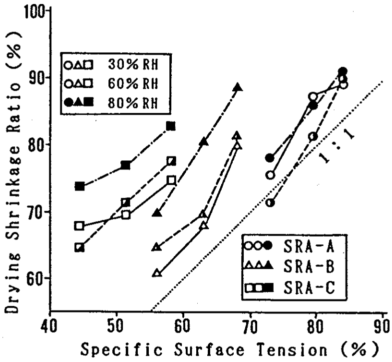

Fig. 8 Relationship between drying shrinkage ratio of mortar and specific surface tension

(2) Surface tension and drying shrinkage

The three types of shrinkage reducing agents were mixed with pure water in the same proportionate amounts for each mortar and the surface tension of the water-SRA solution was measured at 20°C (see Table 3). The results showed that the stronger the concentration, the lower the surface tension; when the concentrations were equal, surface tension decreased in order from SRA-A to SRA-B to SRA-C. The relationship between surface tension and shrinkage is shown in Fig. 8. For SRA-A, specific surface tension and shrinkage ratios are roughly equal. However, for SRA-B and C, specific surface tension and shrinkage ratios show a linear relationship but lower specific surface tension does not correspond to higher drying shrinkage ratios and the effect of lower surface tension does not appear. Thus, if materials having almost the same composition are used, the result is 1:1 or an almost-straight line, as shown in Fig. 4, but when the type of shrinkage reducing agent is varied, the lines diverge widely.

(3) Moisture content of specimen

If humidity conditions for drying are varied (i.e. increased from 40% to 80%), the equilibrium radius of the pore in hardened mortar increases and shrinkage stress decreases. This can be explained by equation (1) shown below. In other words, the pore structures of the specimens are the same and if it is assumed that the specimens prepared under each humidity condition have reached complete equilibrium in moisture content, the pore radius which becomes balanced, is the function of the surface tension of the solution and the humidity.

$$\frac{1}{r} = \frac{RT}{\gamma \; MVf} \mathrm{Ln}(RH) \qquad (1)$$

Here, r is the equilibrium radius of the curvature of the liquid surface, γ is the surface tension of the liquid, M is the molecular weight of the liquid, Vf is the specific volume of the solution, R is the gas constant, T is the absolute temperature and RH is the relative humidity. Using surface tension measurements, the equilibrium radius of the pore is calculated by means of this equation (see Table 4). The equilibrium radius of the pore becomes 4-45Å, depending on surface tension and humidity. Under high humidity conditions where the equilibrium radius of the pore is large, the weight loss of the specimen is clearly smaller. However, when a shrinkage reducing agent has been used where surface tension is low and the equilibrium radius of the pore is expected to be small, no clear difference can be found in the amount of weight loss.

Table 4 Weight loss and calculated equilibrium radius of pore

SRA Type	Dosage (CX%)	Equi.Radius (Å)			Weight Loss (%)		
		30%RH	60%RH	80%RH	30%RH	60%RH	80%RH
Non	0	9.4	20.9	45.3	4.45	3.60	1.27
A	1	7.9	17.5	37.9	4.45	3.68	1.53
	2	7.4	16.6	35.9	4.32	3.55	1.56
	4	6.8	15.2	33.0	4.09	3.52	1.64
B	1	6.4	14.2	30.9	4.61	3.84	1.66
	2	5.9	13.1	28.5	4.54	3.77	1.71
	4	5.2	11.7	25.3	4.37	3.67	1.67
C	1	5.4	12.1	26.2	4.70	3.86	1.64
	2	4.8	10.7	23.2	4.72	3.96	1.73
	4	4.2	9.3	20.1	4.30	3.63	1.74

(4) Equilibrium radius of the pore and drying shrinkage

As described by Chujo, et. al. [1], in a hardened paste having the same pore structure and the same equilibrium radius of the pore, drying shrinkage and the surface tension of the liquid within the pore are comparable. The BET method, in which nitrogen gas is used, was applied for the pastes and the pore volume was calculated from the adsorption isotherm for both pastes, with and without SRA-C. As shown in Fig. 9, almost no difference was observed.

When a shrinkage reducing agent is added, drying shrinkage is calculated through comparison with the control mortar, using the equilibrium radius of the pore and specific surface tension. In other words, under the same equilibrium conditions, since drying shrinkage is simply shown as the surface tension ratio, drying shrinkage of control mortar is multiplied by the specific surface tension to give the drying shrinkage when a shrinkage reducing agent is used. A comparison of calculated and measured figures is shown in Fig. 10.

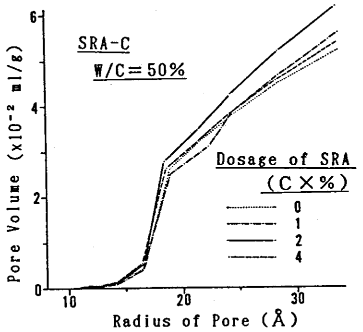

Fig. 9 Pore volume of cement paste with SRA

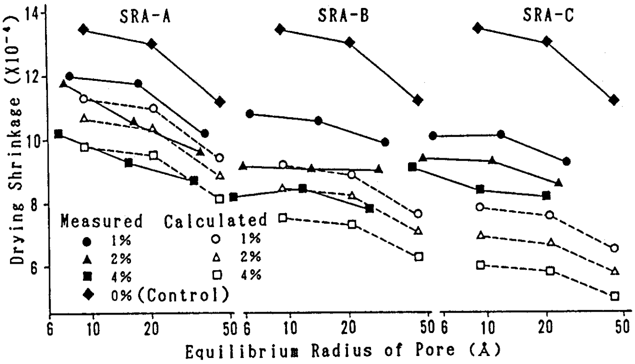

Fig. 10 Comparison of calculated and measured drying shrinkage

When SRA-A is used, measured and calculated values are very similar. This is particularly remarkable when the equilibrium radius of the pore is large. In other words, the lowering in surface tension of the mixing water is continuously maintained in the hardened mortar after drying; in the range up to 4%, the mechanism of shrinkage reduction can be explained by the reduction in surface tension and the reduction in equilibrium radius of the pore. On the other hand, for SRA-C measured values are larger than calculated values and the large functional change in surface tension does not generate a shrinkage reducing effect. For SRA-B, measured values exceed calculated values by about 1×10^{-4}, and are relatively similar.

A difference such as this is thought to be due to the influence of the solubility of the shrinkage reducing agent and molecular weight. SRA-A, with its high solubility and low surfactant activity, reduces surface tension in proportion to the amount used and maintains this condition even after hardening. With SRA-B and SRA-C, however, a small amount is capable of providing a large reduction in surface tension and a great shrinkage reducing effect is developed; but, since solubility is poor, it is thought that surface tension reduction will not continue to increase, even if a larger amount is used.

Chujo, et. al., [1] state that it is stretching facts to define the pore, at a molecular level of 10Å or less, as the equilibrium radius. Since the calculated equilibrium radius of the pore becomes smaller as the surface tension reduction capability increases, this is thought to result in a dissimilarity with the theoretical explanation. This point can be explained by the fact that there is a slight difference between measured and calculated values for SRA-A as well when the equilibrium radius of the pore is small. In addition, as shown in Fig. 9, since there are very few pores of less than 15Å in the hardened paste, it is considered impossible to dispute the quantitative evaluation for the equilibrium radius at this level.

3.3 Concrete Test Results and Discussion

(1) Test results

For the concrete test, ordinary portland cement, tap water, river sand and crushed stone with a maximum size of 20 mm were used. In addition, a resinate air-entraining agent (AE) and an air-entraining water-reducing agent consisting of salts of ligno-sulfonate were used. When SRA was used, air content was controlled to so that the level was equivalent to that of the control concrete. The specimen for drying-shrinkage was 10 x 10 x 40 cm in size. The drying period was sufficiently long to permit drying shrinkage and weight of the specimen to become constant.

Final measurements of the drying shrinkage of concrete were taken, and characteristics of the fresh concrete and compressive strength are shown in Table 5.

Table 5 Results of tests on concrete

SRA Type	Cement Con. $(kg/m^3$	Dosage of SRA (CX%)	M.D.S.[1] $(X10^{-4})$	Weight Loss (%)	Slump (mm)	Air Con. (%)	Comp.Strength (N/mm^2)		
							7days	28days	91days
A	400	0	9.85	2.790	14.0	5.3	34.7	45.8	49.4
		2.5	8.39	2.903	10.0	4.7	35.5	45.6	48.3
		3.75	7.48	2.914	11.0	4.8	35.3	46.1	52.6
		5.0	6.77	2.839	10.5	2.8	34.8	47.9	52.9
		7.5	5.23	2.977	10.0	2.9	29.5	40.9	50.6
	300	0	10.01	3.440	17.0	4.0	2.76	36.7	39.7
		3.33	8.14	3.652	18.5	3.9	24.5	34.2	38.4
		5.0	7.26	3.694	20.0	4.3	22.1	33.2	36.7
		6.67	6.35	3.636	19.5	4.1	20.5	31.3	37.9
		10.0	4.81	3.760	19.0	4.9	17.7	28.0	34.5
B	420	0	11.05	3.825	18.5	3.9	21.9	34.1	42.5
		2.0	8.71	4.494	20.5	3.6	21.3	35.1	43.1
		3.0	7.20	4.488	20.5	3.6	20.3	34.7	41.5
	350	0	10.91	4.106	18.5	3.6	15.5	30.6	36.0
		2.0	8.02	4.641	21.5	3.8	14.2	28.8	36.6
		3.0	7.51	4.720	21.0	3.2	14.3	28.9	37.0
C	300	0	8.84	3.125	11.0	4.5	29.3	39.2	44.3[2]
		2.0	7.01	3.435	16.5	5.8	26.3	36.3	42.8[2]
		2.5	6.63	3.413	13.0	5.4	26.8	37.5	43.5[2]
		3.5	6.31	3.340	13.5	4.9	26.9	37.1	45.0[2]

1) Mesured Drying Shrinkage : Measured ultimately at 18 ,72 and 22 months for SRA-A , B and C ,respectively
2) Evaluated at the age of 6 months

For the most part, drying shrinkage occurred during the six-month to one-year drying period, and no major change was seen after that. As one example, Fig 11 shows changes in drying shrinkage and weight loss occurring as the drying period progresses for SRA-A with a unit cement content of 300 kg/m^3. Drying shrinkage progressed until the drying period had reached approximately six months, after which point almost no further change was observed. No changes in weight or length occurred after six months, and weight and length were considered stable. These conditions held true for all the specimens, regardless of whether a shrinkage reducing agent was added or in what proportion; all 10 x 10 x 40 cm specimens were roughly equivalent in moisture content at the time of final measurement.

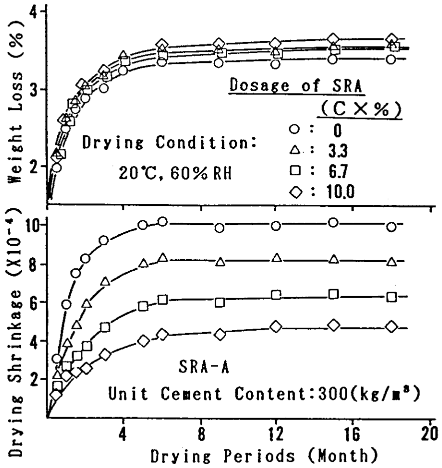

Fig. 11 Changes in drying shrinkage and weight loss

Workability of all concrete specimens was roughly equal, regardless of whether a shrinkage reducing agent was added. In the early stages of aging, compressive strength was slightly lower in cases where a shrinkage reducing agent had been added; however, in the later stages the difference was recovered. This is because the comparatively large volume of organic material added slows down the development of strength, a fact already pointed out with relation to this type of admixture [3].

(2) Type and dosage of shrinkage reducing agent

Fig. 12 shows the relationship between drying shrinkage and type and dosage of shrinkage reducing agent for the final stage of aging. Depending on the amount used, SRA-A shows a linear relationship for shrinkage reduction effect. For a small amount of SRA-B and SRA-C, the effect is remarkable, but when the amount is increased, there is no great increase in effect. This result was also described in the section above regarding mortar tests.

(3) Surface tension and drying shrinkage

The surface tension of the shrinkage reducing agent solution suitable for the specific concrete composition, and the drying shrinkage ratio, are shown in Fig.

13. If this figure is compared with Fig. 8, the results are seen to be similar to those obtained in mortar tests; thus the drying shrinkage mechanism is the same for both concrete and mortar. When the amount of SRA-A is increased to 10%, the drop in specific surface tension reaches its greatest point. However, shrinkage reduction continues to follow a straight line and the amount of shrinkage reduction effect exceeds the reduction in specific surface tension. Use of large amounts of SRA-A does not result in a great decrease in weight loss in specimen and, in theory, equilibrium radius of the pore stays high in comparison to the theoretical value. Therefore, both reduction of surface tension and suppression of moisture volatility contributed to the decrease in drying shrinkage.

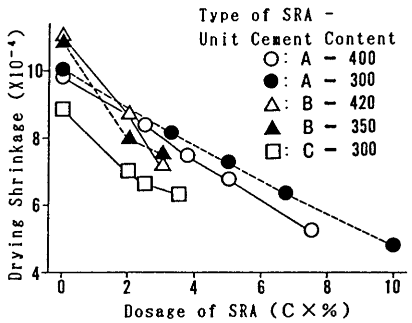

Fig. 12 Relationship between SRA dosage and drying shrinkage of concrete

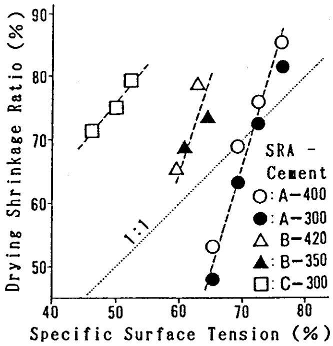

Fig 13 Relationship between drying shrinkage ratio and specific surface tension of concrete

4. CONCLUSION

Various components, particularly alcohol alkylene oxide adducts, were applied and the relationship between surface tension and drying shrinkage in hardened paste, mortar and concrete was studied. The following conclusions were reached in regard to the mechanism of drying shrinkage.

1) Alkylene oxide and lower alcohol are capable of reducing drying shrinkage in cement paste without hindering hydration of cement. They reduce surface tension of the liquid phase and, if they are of similar composition, the degree of reduction of drying shrinkage is proportional to the amount of reduction in surface tension.

2) Alcohol alkylene oxide adducts reduce surface tension and work to reduce drying shrinkage in a wide variety of compositions. Propylene oxide with an average polymerization of 3-6 is added to ethyl, propyl or butyl alcohol shows the greatest reduction in drying shrinkage.

3) The surface tension reduction effect of methyl alcohol ethylene oxide adducts is comparatively small, and the reduction in drying shrinkage is approximately equal to the reduction in surface tension. However, the drying shrinkage ratio cannot be decreased to the equivalent specific surface tension

value for butyl alcohol propylene oxide adducts, which provide greater surface tension.

4) If drying shrinkage for the same equilibrium radius of the pore is estimated on the basis of specific surface tension values, calculated and measured values are roughly equal when methyl alcohol ethylene oxide adducts are used. In particular, where a high-activity surfactant shrinkage reducing agent is used, the measured value is larger than the calculated value. In this way, if a comparatively low-activity surfactant shrinkage reducing agent is used under high humidity conditions, the mechanism of drying shrinkage can be explained through its relationship to surface tension.

5) The relationship between surface tension and drying shrinkage in a concrete specimen is the same as that for mortar. When a high dosage of methyl alcohol alkylene oxide adducts is used, a reduction in drying shrinkage exceeding the specific surface tension is obtained. This is thought to be due to the adducts' additional effect on the suppression of moisture evaporation coupled with its action in reducing surface tension.

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