Effect of Moisture Content on Water Transport in Silica Fume Concrete

by James M. Aldred, S. Swaddiwudhipong, S. L Lee, and T. H. Wee

Silica fume reduced water transport under all test regimens and regardless of initial moisture condition. Ten percent silica fume replacement in concrete with a water-binder ratio (w/b) of 0.6 was found, in general, to have water transport properties similar to ordinary portland cement (OPC) concrete with a w/b of 0.4. Unlike OPC concrete, however, the rate of wick action and moisture flow in silica fume concrete was relatively unaffected by initial moisture content. This suggests that its lower rate of desorption may limit the rate of water transport through saturated silica fume concrete. While water transport properties of silica fume concrete were generally detrimentally affected by the inclusion of a drying cycle and any resultant microcracking, any detrimental influence was similar to or less than that observed with the reference OPC concrete. Accordingly, silica fume concrete did not appear particularly sensitive to microcracking, although it was affected by limited early curing.

Keywords: binder; curing; microcracks; silica fume.

INTRODUCTION

As a result of its pozzolanic reaction and filler effect, silica fume renders the pore structure of the concrete matrix more homogeneous by decreasing the number of larger pores, while the total porosity remains relatively unaffected. Accordingly, silica fume has been found to increase strength and reduce water permeability; the latter is considered to be silica fume’s greatest asset. ACI Committee 234 states that: “the low permeability characteristics of silica fume concrete and the corresponding improvements in long-term durability will provide the single most significant improvement to the concrete construction industry.” Because of the strong and brittle matrix, however, there has been some concern regarding the potential microcracking in concrete containing silica fume, particularly during drying, and the subsequent detrimental effect on concrete properties. Several studies have shown some retrogression in the long-term strength of silica fume concrete. De Larrard and Boistvironnois ascribed this strength reduction to the stresses developed during drying. While there has been considerable research on the effect of drying on mechanical properties of silica fume concrete, little information is available on the water transport properties. Therefore, the degree of the detrimental effect of resultant microcracking is largely unknown.

Gjørv found that a 10% silica fume addition to low-cement content concrete reduced permeability by approximately three orders of magnitude. Hooton showed more modest reductions in permeability at water-binder ratios (w/b) of 0.25; the degree of the reduction in permeability was found to reduce with prolonged curing. Long et al. also showed a greater reduction in permeability in concrete with a w/b of 0.7 compared with one with a w/b of 0.4. Their results also showed that the relative benefit of silica fume replacement was less in specimens subjected to longer curing.

Data on sorptivity with silica fume addition indicate that silica fume does reduce sorptivity. Ramakrishnan and Srinivasan reported a reduction in the water absorption coefficient in fiber-reinforced concrete containing silica fume when compared with the control. Sharafi et al. showed that 10% silica fume reduces 30 min absorption from 2.9 to 1.7%. Morgan also found lower absorption in silica fume concrete. Roy et al. showed no effect of silica fume replacement on initial absorption, while tests by demonstrated a lower sorptivity rate in silica fume concrete, even though the final degree of saturation was the same as for the reference concrete.

Other transport properties are also beneficially modified by the use of silica fume. During drying, Atlassi recorded significant increases in the time to reach equilibrium, especially in relative humidities (RHs) below 80%. Helsing showed that silica fume addition reduced desorption at RHs greater than 30%. Sicard and Pons reported that desiccation shrinkage was reduced by more than 50% when using silica fume. There appears to be little published information on water vapor diffusion through silica fume concrete, but found that silica fume and fly ash addition reduced the rate of moisture flow to approximately 1/3.

RESEARCH SIGNIFICANCE

Research has shown some detrimental effect of microcracking during drying on the mechanical properties of silica fume concrete. Little information, however, is available on the influence of drying on water transport properties. This research examines the effect of drying on a range of transport properties in concrete with and without silica fume.

Parameters involved in water movement under conditions of one-sided drying, as would be found in basements and tunnels, are also included. Silica fume is widely used in such applications, but these data are limited.

EXPERIMENTAL PROGRAM

Concrete materials and mixture proportions

The details of the concrete mixes are given in Table 1. The ordinary portland cement (OPC) had a fineness of 317 m²/kg, a specific gravity of 3.15, and a C₃A content of 8.64%. The fine aggregate consisted of natural sand with a fineness modulus of 2.60 and specific gravity of 2.62. The coarse aggregate was

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crushed granite with a specific gravity of 2.65. The silica fume used had a SiO₂ content of 93% and an approximate fineness of 25,000 m²/kg by nitrogen adsorption. To achieve a target slump of 100 mm, a sulfonated-naphthalene-based water-reducing admixture was added as required.

Test environment
The test environment during testing was controlled within a temperature range of 30 ± 2°C and a RH range of 7.5 ± 5%. This was considered representative of the average ambient conditions within a moist tropical environment. Fans were used to prevent humidity gradients at the surface of specimens being stored under ambient conditions, as well as during testing, which involved ambient drying. The ventilation system provided a minimum evaporation rate for free water of 5.2 x 10⁻⁵ kg/(m²·s), well above the maximum measured evaporation rate from any test specimen.

Sample preparation
Concrete specimens were covered with polythene sheet after casting, demolded within 24 h, and placed in a fog room at 30°C for 28 days to reduce the effect of continued hydration during testing. Some specimens were cured in the fog room for 3 days to determine the effect of limited curing. Prior to testing, specimens had 3 mm removed from the test surfaces by grinding to minimize the gradients associated with cast or troweled finishes. Cast surfaces (that is, cast against formwork) were not assessed in this study. Three types of concrete specimen were used in this study, 145 mm in diameter and nominally 50 or 100 mm in thickness after grinding, and tapered cylinders 100 to 110 mm in diameter and nominally 180 mm in thickness after grinding. The 50 mm thick specimens had a surface area-volume ratio (SA/V) of 0.7 cm⁻¹, while the 100 and 180 mm thick specimens had a SA/V of 0.5 cm⁻¹.

The drying procedure attempted to simulate drying conditions in the field without the problem of inducing severe microcracking by drying at 105°C or the inconvenience of prolonged ambient drying. Dried specimens were oven-dried at 40°C and 45% RH for 14 days, then left in well-ventilated racks within the test environment for an additional 14 days. The changes in mass during this drying procedure for 100 mm thick specimens (SA/V = 0.5) are shown in Fig. 1, and those for long-term ambient drying of smaller specimens (SA/V = 1.4) are shown in Fig. 2. It can be seen that the mass of all specimens increased slightly after oven drying due to adsorption of ambient humidity. After the drying procedure, the OPC specimen with a w/b of 0.6 appeared to have reached the apparent equilibrium level attained by prolonged ambient drying. The other specimens were between 75 and 80% of their respective apparent equilibria. It is interesting to note that the absolute mass loss from the silica fume concrete at apparent equilibrium was significantly less than the OPC concrete for both w/b. This is presumably due to the finer pore structure within hydrated silica fume concrete that prevents drying at ambient humidity of pores below a critical radius based on the Laplace equation.

Saturated specimens were taken from the fog room and immersed in water for a minimum of 24 h before testing.

![Fig. 1 - Mass changes during 28-day drying procedure (Specimens SAN = 0.5 cm⁻¹).](image1)

![Fig. 2 - Mass changes during prolonged ambient drying (Specimens SAN = 1.4 cm⁻¹).](image2)

### Table 1 - Concrete mixture proportions and strength

<table>
<thead>
<tr>
<th>Mixtures</th>
<th>w/c (OPC)</th>
<th>Cement (OPC)</th>
<th>Silica fume, kg/m³</th>
<th>Fine aggregate, kg/m³</th>
<th>Coarse aggregate, kg/m³</th>
<th>28-day strength, N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>0.6</td>
<td>300</td>
<td></td>
<td>825</td>
<td>257</td>
<td>770</td>
</tr>
<tr>
<td>SF 10</td>
<td>0.6</td>
<td>270</td>
<td>30</td>
<td>825</td>
<td>257</td>
<td>770</td>
</tr>
<tr>
<td>OPC</td>
<td>0.4</td>
<td>400</td>
<td>—</td>
<td>765</td>
<td>267</td>
<td>790</td>
</tr>
<tr>
<td>SF 5*</td>
<td>0.4</td>
<td>380</td>
<td>20</td>
<td>765</td>
<td>267</td>
<td>790</td>
</tr>
<tr>
<td>SF 10</td>
<td>0.4</td>
<td>360</td>
<td>40</td>
<td>765</td>
<td>267</td>
<td>790</td>
</tr>
</tbody>
</table>

*SF 5 only tested for water absorption, sorptivity, desorption, and cumulative inflow.
During the experimental setup, great care was taken to ensure that the test surface was kept saturated until testing. This procedure would simulate conditions where concrete was unable to dry before exposure.

Vacuum saturated specimens were dried as discussed previously before being subjected to a vacuum of approximately 1 mm Hg for 3 h, submerged in deaerated water under vacuum for a further hour, and then left submerged at atmospheric pressure for 2 days. The procedure was similar to the sample preparation requirements of ASTM C1202-97.²³

Permeability test

Tapered cylindrical specimens were subjected to a constant hydraulic pressure of 4.0 N/mm² using deaerated water, as shown in Fig. 3. The permeability was based on the rate of outflow or the rate of inflow after 50 days if outflow was not achieved.

Water absorption test

Water absorption was measured on cores taken from cubes cured for 3 and 28 days according to BS 188: Part 122: 1983,²⁴ except that the temperature of the water was 30 ± 1 C rather than 20 ± 1 C.

Sorptivity test

After the test specimens 145 mm in diameter and 100 mm thick had been dried as previously described, they were sealed into a polyvinyl chloride (PVC) sleeve with epoxy paste and tested with 20 mm of water on the test surface, similar to the wick action test procedure given as follows. Water absorbed into the specimen was measured by removing excess water and weighing to the nearest 0.01 g on an electronic balance. Sorptivity was calculated from mass gain measurements taken daily up to 14 days. The sorptivity value is the slope of the line of best-fit for mass gain over a sectional area plotted against the square root of time.

Desorption test

Desorption was measured on concrete cylinders, 145 mm in diameter and 100 mm thick, sealed into PVC sleeves on a polymethyl methacrylate base plate, with its exposed face kept moist, and covered with polymethyl methacrylate. When the sealant had hardened, the top polymethyl methacrylate plate was removed along with any excess water. The specimen, together with the cell, was weighed immediately and then placed in the racks to dry from the exposed face. The specimen was weighed daily until 14 days. Mass loss was assumed to be entirely due to moisture loss from the concrete.

Desorption values are reported as the slope of the line of best-fit for mass loss per unit area plotted against the square root of time in hours, as they were for the sorptivity values.

Water vapor diffusion test

The cell used to measure water vapor diffusion was similar to that used by Buenfeld et al.¹⁹ Fifty mm thick specimens of 145 mm diameter were sealed into the test cells. The top surface of the specimen was exposed to the 75% RH test environment, with the bottom surface controlled near 0% RH (using silica gel). The test setup is shown in Fig. 4. Vapor diffusion through the specimen was monitored by weighing the cell until a steady rate of weight gain was achieved (i.e., water absorption by the silica gel). The water vapor diffusion coefficient was calculated using Fick’s first law.

Moisture flow test

Tests were also conducted on moisture flow through concrete specimens where the humidity gradient was from approximately 100% inside the cell to 75% within the test environment. The test cell was the same as shown in Fig. 4, but water, instead of silica gel, was placed within the cell. Weight loss from the cell was measured until a steady rate of loss was achieved. The moisture flow coefficient was calculated using Fick’s-first law.

Wick action test

Two separate wick action test methods were adopted. The first was based on outflow, and was similar to that developed by Buenfeld et al.¹⁹ Dried and saturated specimens 145 mm diameter and 100 mm thick were sealed into the test cell. Approximately 20 mm of water was poured onto the top surface of the concrete specimen. The test details are shown in Fig. 5. Mass loss, which was assumed to be entirely water loss, was measured to the nearest 0.01 g. A steady rate of mass loss was achieved after approximately 100 days, as had also been observed by Buenfeld et al.¹⁹

The second test method was based on inflow. Concrete specimens 100 mm in thickness were sealed into a test cell using epoxy paste. Water was applied to the bottom of the specimen, and the volume of inflow was measured in a similar fashion to the initial surface absorption test to an accuracy of 0.8 microliters using a capillary tube. A steady rate of inflow was established after approximately 70 days, and variability was reduced compared with the first wick action procedure.

![Fig. 3—Water permeability test setup.](image)

![Fig. 4—Water vapor diffusion cell.](image)
RESULTS

A summary of transport properties of saturated and dried concrete with and without silica fume is given in Table 2.

Permeability

Permeability results for the w/b of 0.6 are presented in Fig. 6 and demonstrate that the permeability appeared stable between 10 and 20 days, suggesting there was no significant effect of continued hydration. Figure 7 summarizes the permeability data for concrete with and without 10% silica fume at both w/b. Silica fume addition was found to reduce permeability at both w/b and under initially saturated and dried conditions. The reduction in permeability was more pronounced at the lower w/b. The drying process significantly increased water permeability for OPC concrete and concrete containing silica fume at both w/b. The increase in permeability was by approximately an order of magnitude for the higher w/b, and less for the lower w/b. There was no indication that concrete with silica fume replacement was more sensitive to drying. On the contrary, the silica fume concrete with a w/b of 0.4 was least affected by drying, presumably due to its lower rate of desorption, as discussed as follows.

Water absorption

The absorption results are shown in Fig. 8. Silica fume replacement had no significant influence on water absorption at the higher w/b, but reduced water absorption at both 5 and 10% replacement for a w/b of 0.4. Under conditions of 3 days curing, the absorption for the 10% silica fume replacement at both w/b of 0.6 and 0.4 was higher than for the 28-day curing period, as would be expected. Limited curing, however, was not found to detrimentally influence absorption compared with the reference concrete, as has been found for more slowly hydrating pozzolans such as blast-furnace slag and fly ash.26

Sorptivity

Unlike the absorption result, silica fume replacement was found to significantly reduce sorptivity at both w/b, as shown in Fig. 9. The reduction in sorptivity was 65% for 10% replacement at a w/b of 0.6, and 47 and 73% for 5 and 10% replacement, respectively, at a w/b of 0.4. Ten percent silica fume replacement at a w/b of 0.6 gave comparable sorptivity to the reference concrete at a w/b of 0.4.

Desorption

The rates of desorption for concrete with and without silica fume replacement are presented in Fig. 10. Desorption was found to be linearly related to the square root of time for silica fume concretes with correlation coefficients of 0.99 or higher. Silica fume was found to reduce the desorption rate to approximately 25% that of the reference OPC concrete in the case of 10% replacement, and 44% in the case of 5% replacement. The rates of desorption ranged from 38 to 65% of the corresponding sorptivity values. A similar relationship between desorption and sorptivity was observed for the ref-
ference concrete, where the range was 43 to 62%. This suggests that the reductions in rates of sorptivity and desorption achieved by silica fume replacement may be due to the same effect on pore size distribution. A completely different relationship between these two parameters has been reported for hydrophobic and blast-furnace slag concrete that suggests different mechanisms of influencing rates of wetting and drying.27

**Water vapor diffusion**

The water vapor diffusion coefficients were found to be virtually unaffected by silica fume replacement at a w/b of 0.6 (Fig. 11), and reduced slightly in the case of a w/b of 0.4. While there was no significant difference between the coefficients for dried and saturated specimens at the higher w/b, the saturated concrete with a w/b of 0.4 did appear to have a lower vapor diffusion coefficient. Perhaps the drying procedure may have removed water from some capillary pores in addition to those dried during the vapor diffusion test itself. Additional air-filled pores may have provided pathways for water vapor diffusion, resulting in a higher measured rate of diffusion.

**Moisture flow**

Figure 12 demonstrates that the presence of silica fume profoundly reduced moisture flow. The reduction, compared with the control, was up to one order of magnitude. Unlike the control concrete, there was no apparent effect of initial moisture content on moisture flow through concrete with 10% silica fume replacement. The rate of moisture flow for the 3-day cured specimens was similar to the better-cured dried and saturated specimens. This is in marked contrast to the relative rates of wick action for these specimens described as follows.

**Wick action**

The rates of wick action for saturated and dried concrete with and without silica fume are given in Fig. 13 and 14. Silica fume replacement significantly reduced wick action for both w/b. The reduction was more marked in concrete with the higher w/b. Again, unlike reference concrete, the rate of wick action through concrete with silica fume replacement appeared to be relatively unaffected by initial moisture content. Limited curing of 3 days for the higher w/b concrete was found to increase the rate of wick action significantly. The rate, however, progressively reduced throughout the experiment to a level comparable with that of the dried OPC concrete. In fact, the rate appeared to be continuing to reduce even after nearly 1 year of testing.

While the outflow procedure did show the general trend for the wick action rate for 10% silica fume replacement in concrete with a w/b of 0.4, it was apparent that it was not accurate enough to differentiate between concrete of similar high quality. Hence, the inflow method was adopted to compare the effect of 5 and 10% replacement with silica fume in concrete with a w/b of 0.4. The cumulative water inflow results for saturated, dried, and vacuum-saturated control specimens, as well as those with 5 or 10% replacement, are shown in Fig. 15.

Silica fume replacement reduced cumulative water inflow when compared with the OPC control under all conditions. The reduction for saturated specimens was 71 and 81% for 5 and 10% silica fume replacement, respectively; for dried

![Fig. Y-Fourteen-day sorptivity of concrete with and without silica fume replacement.](image)

![Fig. 12—Moisture flow coefficients for concrete with and without silica fume replacement (w/b = 0.6).](image)

![Fig. II-Water vapor diffusion coefficients for concrete with and without silica fume replacement (w/b = 0.6).](image)
specimens, 56 and 69%; and for vacuum saturated specimens, 67 and 74%. The reduction in inflow achieved by 5% silica fume replacement was only slightly less than that for 10% replacement. Indeed, the data show that the early inflow into concrete with 5 and 10% silica fume replacement were similar, but at later stages, the rate for the 5% replacement concrete became greater. At both replacement levels, the relative behavior of saturated, dried, and vacuum-saturated specimens were similar. The higher inflow for the dried specimens is to be expected during the initial stages due to the effect of absorption. The continued higher rate after initial absorption suggests that there may be continued filling of finer pores after the constant penetration depth had been established. The rate of inflow for the vacuum-saturated specimens became greater than that for the saturated specimens, even though they were initially similar. This indicates that the drying cycle had a detrimental effect on the pore structure; however, its relative influence on wick action was not markedly different than that for the control.

**DISCUSSION**

Silica fume replacement was found to reduce water transport at both w/b's being studied. Generally, the relationship among the various transport parameters was similar to that expected for an OPC concrete of higher quality. This suggests that the changes in transport properties, as a result of

<table>
<thead>
<tr>
<th>Water transport parameter</th>
<th>OPC, w/b = 0.6</th>
<th>SF 10%, w/b = 0.6</th>
<th>OPC, w/b = 0.4</th>
<th>SF 10%, w/b = 0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability coefficient, m/s&lt;br&gt;Saturated</td>
<td>5.14 \times 10^{-13}</td>
<td>8.78 \times 10^{-14}</td>
<td>6.76 \times 10^{-14}</td>
<td>8.47 \times 10^{-17}</td>
</tr>
<tr>
<td>Dried</td>
<td>7.01 \times 10^{-12}</td>
<td>2.02 \times 10^{-12}</td>
<td>4.99 \times 10^{-13}</td>
<td>2.11 \times 10^{-16}</td>
</tr>
<tr>
<td>British Standard absorption, % dry mass&lt;br&gt;3-day cure</td>
<td>4.4</td>
<td>4.1</td>
<td>3.4</td>
<td>2.2</td>
</tr>
<tr>
<td>28-day cure</td>
<td>3.2</td>
<td>3.6</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td>14-day sorptivity&lt;br&gt;Correlation coefficient</td>
<td>0.223</td>
<td>0.079</td>
<td>0.066</td>
<td>0.018</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.998</td>
<td>0.996</td>
<td>0.999</td>
<td>0.972</td>
</tr>
<tr>
<td>14-day desorption&lt;br&gt;Correlation coefficient</td>
<td>0.138</td>
<td>0.030</td>
<td>0.048</td>
<td>0.012</td>
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<tr>
<td>Correlation coefficient</td>
<td>0.996</td>
<td>0.997</td>
<td>0.998</td>
<td>0.994</td>
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<tr>
<td>Water vapor diffusion, m²/s&lt;br&gt;Saturated</td>
<td>10.23 \times 10^{-8}</td>
<td>9.62 \times 10^{-8}</td>
<td>—</td>
<td>2.25 \times 10^{-8}</td>
</tr>
<tr>
<td>Dried</td>
<td>9.85 \times 10^{-8}</td>
<td>9.28 \times 10^{-8}</td>
<td>4.76 \times 10^{-8}</td>
<td>3.21 \times 10^{-8}</td>
</tr>
<tr>
<td>Moisture flow coefficient, m²/s&lt;br&gt;Saturated</td>
<td>2.01 \times 10^{-8}</td>
<td>3.39 \times 10^{-7}</td>
<td>—</td>
<td>2.81 \times 10^{-8}</td>
</tr>
<tr>
<td>Dried</td>
<td>9.63 \times 10^{-7}</td>
<td>3.96 \times 10^{-7}</td>
<td>5.07 \times 10^{-7}</td>
<td>2.72 \times 10^{-8}</td>
</tr>
<tr>
<td>Wick action, (1 \times 10^{7} kg/(m²/s)&lt;br&gt;Saturated</td>
<td>593.8</td>
<td>51.2</td>
<td>90.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Dried</td>
<td>216.5</td>
<td>71.9</td>
<td>70.6</td>
<td>5.3</td>
</tr>
</tbody>
</table>
silica fume replacement, were associated with the increased density and pore refinement of the hydrated matrix, as has been concluded by ACI234R-96.\textsuperscript{2}

Under conditions of one-sided drying, however, silica fume concrete did behave differently than pure OPC concrete. While there was a significant influence of initial moisture content on wick action and moisture flow in OPC concrete, there was no such effect on silica fume concrete. For example, the moisture flow coefficients for saturated, dried, and 3-day cured specimens were virtually the same, and all significantly lower than that for dried OPC concrete with a \( w/b \) of 0.4. This was despite both the comparable permeability of these two mixtures and the water vapor diffusion for the silica fume concrete being significantly higher. Perhaps the pore structure of the hydrated silica fume paste provided a greater surface area for adsorption that reduced the rate of drying. Certainly, the desorption value for the silica fume concrete (\( w/b = 0.6 \)) was lower than that for the OPC (\( w/b = 0.4 \)), even though its sorptivity was higher.

Another influence could have been that the drying procedure resulted in a relatively greater moisture content for specimens containing silica fume, due to their greater resistance to drying. The difficulties associated with drying concrete of high quality were discussed by Tang and Nilsson.\textsuperscript{28} While this may have been a factor, this hypothesis does not appear completely satisfactory. The more porous silica fume concrete with a \( w/b \) of 0.6 did lose 3.1% of its dry mass during the drying procedure, and yet also exhibited the same phenomenon.

Tests on water inflow into saturated and vacuum-saturated silica fume concrete (Fig. 15) showed that there was an increase in the rate of wick action associated with the inclusion of a drying cycle. If wick action is a function of desorption from the drying surface sucking water through the specimen, this increase could be explained by the higher permeability of the vacuum-saturated concrete facilitating greater flow to the evaporation front.

There was no indication of a disproportionate reduction in quality of concrete containing silica fume subjected to a drying cycle. Indeed, silica fume replacement at the lower \( w/b \) appeared relatively unaffected by the drying cycle. As mentioned previously, this may have been in part due to the difficulty of establishing a uniform moisture condition within the concrete with the 28-day drying procedure adopted. This procedure, however, did result in mass loss equivalent to 77% of that expected for prolonged ambient drying to apparent equilibrium for the silica fume concrete with a \( w/b \) of 0.4, comparable with that for the OPC control at 80%. Nonetheless, the absolute mass loss for silica fume concrete at apparent equilibrium was significantly less than that for the control, and may have been the reason for its better relative performance.

If the reduced absolute moisture loss was due to a finer pore structure, a similar reduction in mass loss at equilibrium would be expected in the field, provided that the drying conditions were not more severe. Accordingly, similar relative improvement in transport properties after drying may be expected. The degree of drying obtained by conditioning a small concrete specimen in a ventilated oven at 40°C for 14 days and ambient drying for a further 14 days would be greater than that expected for an actual structural member under most exposure conditions. Consequently, the concerns regarding the possibility of microcracking as a result of drying causing problems with properly mixed and cured silica fume concrete appear unsupported by these results. It is important to note that this study only considered one drying cycle. Silica fume concrete exposed to multiple wetting/drying cycles may behave differently.

One area of possible concern highlighted by these data is the performance of silica fume concrete of higher \( w/b \) receiving limited curing, as seen in Fig. 13. The rate of wick action in such concrete was initially six times greater than the dried specimens cured for 28 days, and even higher than the control. This rate did reduce consistently through the duration of the test, indicating that hydration processes were continuing. It is interesting to note that 1 year of one-sided wetting following drying after 3 days curing was unable to reduce the rate of wick action to the same level as that for concrete that had initially received 28 days curing before drying. Exposure tests by Ho and Mak\textsuperscript{29} also found that the time to improve concrete properties after early drying to be protracted. ACI234R-96\textsuperscript{2} recommends that silica fume concrete be kept "wet for at least 3 days, and preferably for 5 to 7." Three days of fog room curing may be termed limited curing within a laboratory context, but it is better than 3 days with burlap and plastic on a typical job site. The wick action data suggest that caution may be necessary in the use of silica fume where the quality and duration of curing cannot be assured. Fortunately, the tests on wetting and drying showed that even the 3-day cured specimens had reduced chloride penetration when compared with a control.\textsuperscript{27}

**SUMMARY AND CONCLUSIONS**

Based on the experimental data presented in this paper, the following conclusions can be drawn:

1. Silica fume replacement significantly reduced water transport through well-cured concrete under all test conditions;
2. With regard to water penetration, concrete with silica fume replacement appeared less sensitive to microcracking as a result of drying than the control concrete without silica fume; and
3. Limited curing of silica fume concrete with a higher \( w/b \) before exposure resulted in an increased rate of wick action, suggesting that care must be taken to ensure adequate curing and that a minimum recommendation of 3 days of moist curing may be insufficient under certain conditions.

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