Influence of Pumping on Characteristics of Air-Void System of High-Performance Concrete

R. PLEAU, M. PIGEON, A. LAMONTAGNE, AND M. LESSARD

The results of an experimental study in which a high-performance air-entrained concrete mixture (water-cement ratio = 0.29; 28-day average compressive strength of 75 MPa) was pumped at the job site horizontally and vertically are presented. Concrete specimens were taken before and after pumping. The specimens were subjected to the ASTM C 457 microscopical determination of the characteristics of the air-void system. The size distribution of the air voids was also recorded using a computer-assisted image analysis system. The study results indicate that pumping can reduce the total air content and increase the air-void spacing factor. It was observed that the loss of air is mainly due to a very significant decrease of the number of small air voids (<100 μm in diameter); the number of larger voids is very little modified. This suggests that the frost durability may be more detrimentally affected than it first appears, when only the air content and the spacing factor are considered. It was also found that the loss of small air voids is more important for vertical pumping than for horizontal pumping, probably because the pumping pressure involved is higher. A mechanism is proposed to explain the observed effect of pumping on the characteristics of the air-void system.

Field experience indicates that pumping often reduces the total air content in air-entrained concrete (*1–4*), which can possibly have a detrimental influence on the frost resistance. The air loss is generally small (i.e., 1 to 2 percent, but it can also be significant (i.e., greater than 4 percent). Lowering the air content generally yields a higher value of the air-void spacing factor, but very little data are available on the influence of pumping on the value of the spacing factor. Three mechanisms can explain the loss of air during pumping (*4*):

- Dissolution of air into the mixing water as a result of the higher solubility at a higher pressure,
- Vacuum effect occurring when the concrete falls in the descending portion of the hose, and
- Impact when the concrete drops from a given height at the end of the hose.

Previous work indicates that for ordinary concretes the decrease of the total air content is mainly due to the last two mechanisms. However, a recent study by Elkey et al. (*4*) clearly indicates that the first mechanism (dissolution of air) can cause a significant reduction in the total number of voids contained per unit volume even without a significant reduction of the total air content.

The necessity of air entrainment to protect high-performance concretes (HPCs) against freezing and thawing cycles is still disputed. It is clear, however, that many HPCs require at least a minimum amount of entrained air to be frost resistant (*5,6*), which means that these concretes could be detrimentally affected by a loss of air due to pumping. No data have been found on the influence of pumping on the air-void system of HPC. The aim of the present study was to provide such data.

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TEST PROGRAM

The test program was conducted during the construction of a highway bridge built with an HPC having a water-cement ratio of 0.29 and a 28-day average compressive strength of 75 MPa. The specified composition of the concrete mixture is given in Table 1. At the job site, the fresh concrete was discharged and pumped directly into the formwork. Two series of concrete specimens (from two distinct batches) were prepared. In the first series, the concrete was pumped horizontally over a distance of approximately 20 m. In the second series, the concrete was pumped to a height of about 20 m before being discharged 5 to 7 m lower. In both series, specimens were prepared immediately before and after pumping. All concrete specimens were subjected to the ASTM C 457 microscopical examination (modified point count method) to assess the characteristics of the air-void system in the hardened concrete. For each specimen, 3,200 point counts were regularly spaced along a line of traverse of 240 cm covering a surface of 144 cm^2. The size distributions of the air-void circular sections seen under the microscope were also recorded using a computer-assisted image analysis system. For each specimen, the sections having a diameter smaller than 300 μm were measured and counted on 50 images covering a total surface of 2.84 cm^2.

A numerical method described elsewhere (*7,8*) was used to determine the size distribution of the air voids contained in a unit volume of concrete and the flow length (i.e., the distance between a point chosen at random into the cement paste and the boundary of the nearest air void). The flow length (Q) is similar to the Philleo factor (*9*), and it physically corresponds to the distance that freezable water must travel to reach an escape boundary during freezing. It is closely related to the frost resistance of concrete (*8*) and provides a much better evaluation of the efficiency of the air-void system than the commonly used ASTM C 457 spacing factor.

TEST RESULTS

The air content measured in the fresh concretes (ASTM C 231) and the characteristics of the air-void system in the hardened concretes

TABLE 1 Specified Composition of the Concrete Mixture

Water (kg/m³)	Cement* (kg/m³)	Fine Aggr. (kg/m³)	Coarse Aggr. (kg/m³)	Super-plasticizer (L/m³)	Air-Entraining Agent (mL/m³)	Set-Retarding Admixture (mL/m³)
130	450	700	1000	7.5	300 to 350	450

* Portland cement with silica fume (7% by weight)

(ASTM C 457) are presented in Table 2. This table indicates that the air content measured in the fresh concrete before pumping was almost the same for the two concrete batches (5.9 versus 6.4 percent). It also shows that a small air loss (0.9 and 0.4 percent) occurred during the transportation from the plant to the job site. That the air contents measured in the hardened concrete are lower than those measured in the fresh concrete is not uncommon, but it could suggest that some loss of air occurred from the time of casting to the final set of cement paste.

For the specimens subjected to horizontal pumping, the data in Table 2 show that the air content measured in the hardened concrete before pumping (4.3 percent) is relatively low. The air-void system, however, can be considered excellent because the specific surface of the air voids is very high (33.6 mm^{-1}), and the spacing factor (160 μm) is much lower than the maximum value of 230 μm recommended by the Canadian Standard CSA A23.1 (*10*). After pumping the air content is approximately the same (4.7 versus 4.3 percent), but the specific surface decreases significantly (from 33.6 to 23.1 mm^{-1}) and the spacing factor increases to a value (225 μm), very close to the 230 μm limit.

For the specimens subjected to vertical pumping, the data in Table 2 show that, even if the air content before pumping is significantly higher than in the specimens subjected to horizontal pumping (5.6 versus 4.3 percent), the specific surface is much smaller (21.8 versus 33.6 mm^{-1}), and the spacing factor is significantly higher (205 versus 160 μm). Nevertheless, the air-void system before pumping can still be considered satisfactory. Table 2 indicates however that after vertical pumping the air-void system is not satisfactory because the air content drops from 5.6 to 3.6 percent, the specific surface remains approximately the same (21.6 versus 21.8 mm^{-1}), and the spacing factor increases from 205 μm to 265 μm, a value clearly over the 230 μm limit. It is interesting to note that this increase in the spacing factor is similar to that due to horizontal pumping.

Figures 1 and 2 show the size distributions of air-void sections per unit surface of concrete observed under the microscope for the concrete specimens subjected to horizontal and vertical pumping, respectively. According to the data in these figures, which were obtained with the image analysis system, pumping reduces the number of air-void sections having a diameter smaller than 100 μm, but the size distribution of the larger sections is little modified. This effect is more important when concrete is subjected to vertical pumping instead of horizontal pumping.

Figures 3 and 4 show the size distributions of air voids for the concrete specimens subjected to horizontal and vertical pumping, respectively, as obtained from the mathematical relationship between the size distribution of a system of spheres randomly dispersed in a volume and the projection of this system on a planar surface (*7*). According to the data in these figures, horizontal pumping only slightly reduces the number of air voids smaller than 100 μm in diameter, but vertical pumping reduces the number of voids smaller than 100 μm significantly. It can be seen in Figure 4 that the number of voids smaller than 50 μm becomes extremely small after vertical pumping.

Figures 5 and 6 show the statistical distribution of the flow length as computed assuming that all the air voids are randomly dispersed throughout the cement paste. As mentioned previously, this flow length corresponds physically to the distance between a point chosen at random in the cement paste and the boundary of the nearest air void. The area under the curve from 0 to any given flow length value is equal to the probability that the flow length is smaller or equal to that value. The total area under the curve is obviously equal to 1.0 because the probability that the flow length is smaller than infinity is 100 percent. According to these test results, horizontal

TABLE 2 Air Content in Fresh Concrete (ASTM C 231) and Characteristics of the Air-Void System in Hardened Concrete (ASTM C 457)

		Fresh Concrete	Hardened Concrete		
		Air Content (%)	Air Content (%)	Specific Surface (mm^{-1})	Spacing Factor (μm)
Horizontal pumping	At plant	6.8	—	—	—
	Before pumping	5.9	4.3	33.6	160
	After pumping	6.1	4.7	23.1	225
Vertical pumping	At plant	6.8	—	—	—
	Before pumping	6.4	5.6	21.8	205
	After pumping	4.8	3.6	21.6	265

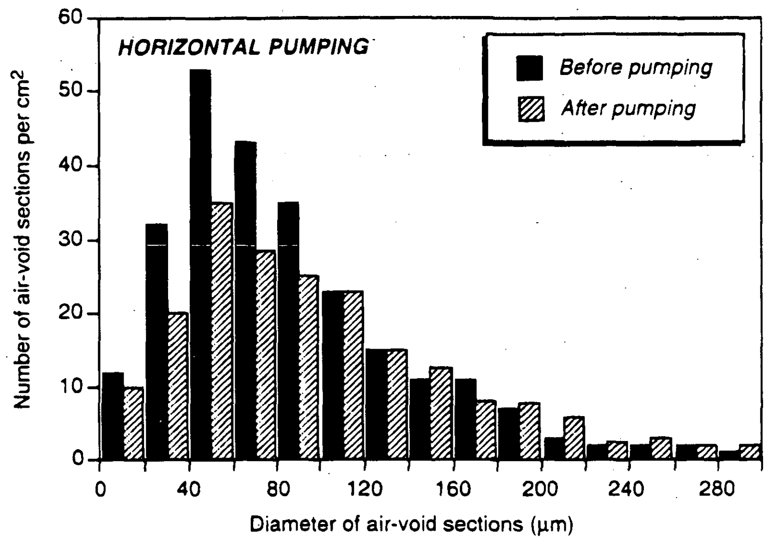

FIGURE 1 Size distributions of sections of air voids observed under microscope for specimens subjected to horizontal pumping.

pumping only slightly increases the probability of having a higher flow length, but vertical pumping has a more significant influence. After vertical pumping, a significant fraction of the cement paste is located much farther from the nearest air void.

Table 3 summarizes the characteristics of the air-void system of the various specimens when only the air voids smaller than 300 μm in diameter are taken into account. In this table, the flow length is associated with a probability level of 98 percent (i.e., only 2 percent of the cement paste is located at a distance larger than this value from the perimeter of the nearest air void). Although for the specimens subjected to horizontal pumping, the number of air voids is reduced by about 25 percent (31,400 to 23,900 voids/cm^3), the characteristics of the air-void system (air content and flow length) are not significantly modified. However, for the specimens subjected to vertical pumping, the number of voids per cm^3 of concrete and the air content are roughly reduced to half of their initial values, and the flow length increases by about 75 percent (from 175 to 305 μm).

DISCUSSION OF RESULTS

The test results described are interesting in many ways. First, they indicate that in certain cases pumping can have a small effect (as it was found for horizontal pumping) or sometimes a significant detrimental effect (as it was found for vertical pumping) on the characteristics of the air-void system. Second, they provide valuable information on the mechanisms of air loss due to pumping and the influence of various parameters. Third, they point the way to further research to understand

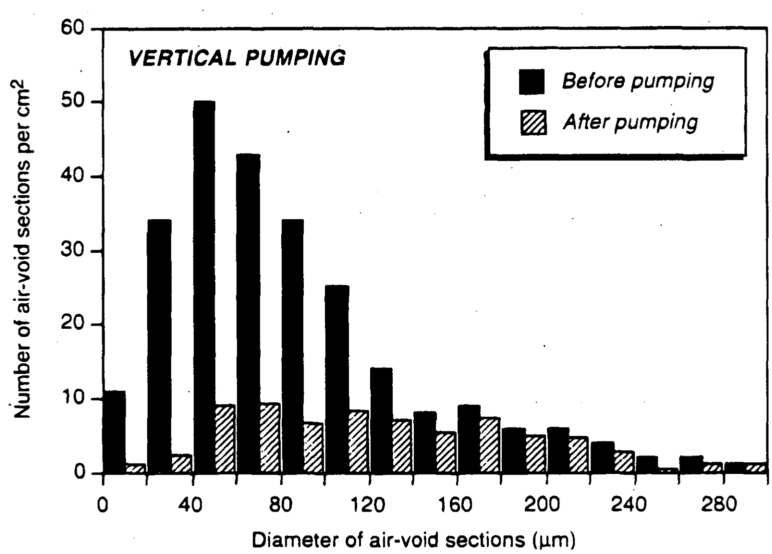

FIGURE 2 Size distributions of sections of air voids observed under microscope for specimens subjected to vertical pumping.

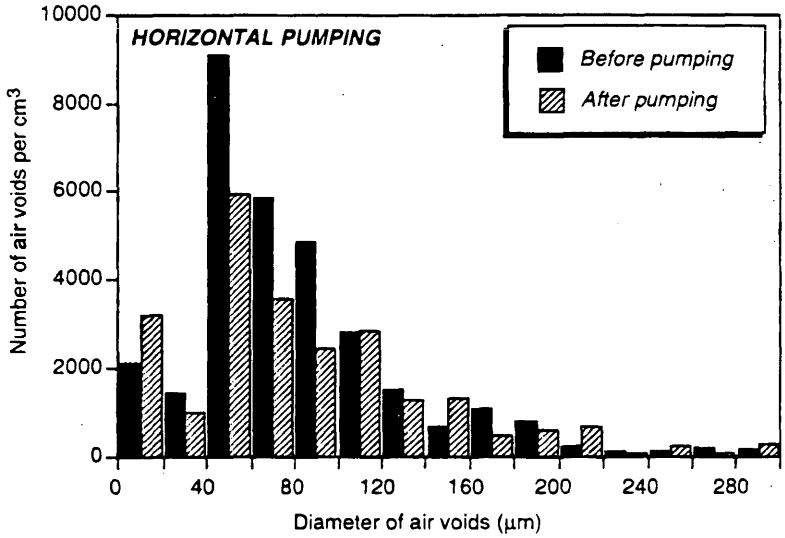

FIGURE 3 Size distributions of air voids obtained for specimens subjected to horizontal pumping.

and predict the influence of pumping on the characteristics of the air-void system and thus on the frost durability of concrete.

Field experience and laboratory investigations indicate that, most of the time, the loss of air during pumping is mainly due to the falling of concrete. In the pumping hose, falling creates a vacuum effect, and air voids can also break when concrete violently hits the formwork or the concrete already in place (*1–3*). The lowering of the falling height and the adding of an elbow pipe in the descending part of the pumping hose were found to be two efficient ways to attenuate this problem. It appears clear, however, that the loss of air caused by the falling of concrete is mainly because of the loss of large air voids, whereas the number of small air voids (<300 μm in diameter) is little affected. The pressure inside an air void is inversely proportional to its diameter. This pressure is roughly equal to the atmospheric pressure (≈100 kPa) inside the larger voids, but it can reach values as high as 250 kPa inside the smaller ones (≈10 μm in diameter) (*11*). It follows that, because of their higher internal pressure, smaller air voids are less vulnerable to the vacuum or the breaking mechanism. Even if the air losses due to these mechanisms are annoying for the site engineer, it is unlikely that they significantly influence the real spacing of the air voids and, consequently, the frost resistance of concrete.

The dissolution of air in the surrounding mixing water appears to be a more important concern. Because the pumping pressures used at job sites typically range from 1,500 to 3,000 kPa and because the solubility of air increases linearly with the pressure, the rate of dissolution of air is dramatically increased during the pumping of concrete. The dissolution process affects the smaller air voids more than

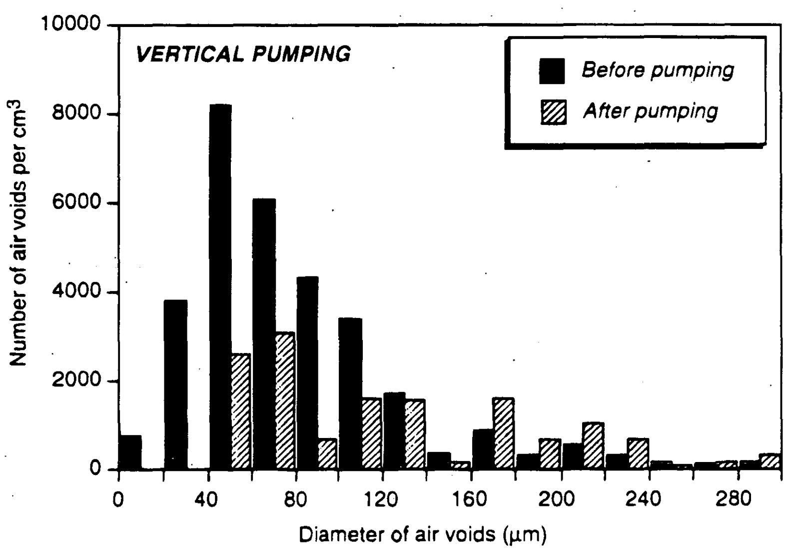

FIGURE 4 Size distributions of air voids obtained for specimens subjected to vertical pumping.

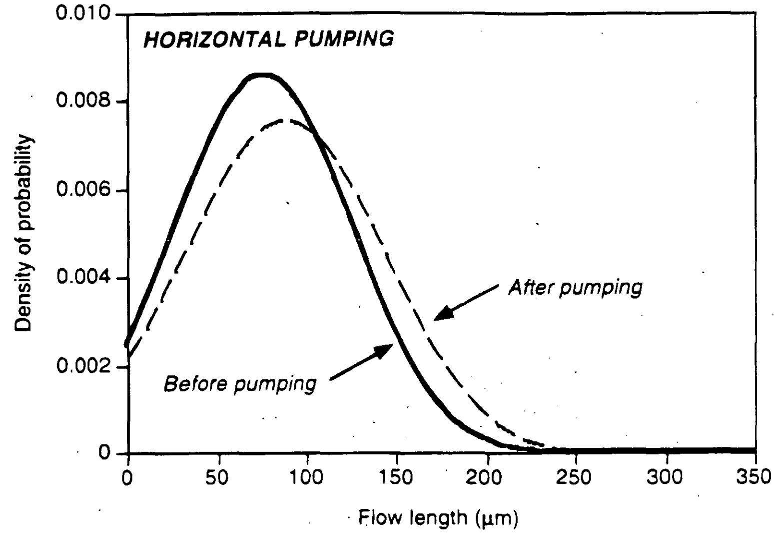

FIGURE 5 Statistical distributions of flow length obtained for specimens subjected to horizontal pumping.

the larger ones because their specific surface is higher (which speeds up the exchanges at the gas-liquid interface) and because their initial volume is smaller. At the end of the pumping hose, the pressure is released, the mixing water becomes oversaturated in air and, consequently, part of the dissolved air comes back into the existing voids. Assuming that the pressure was not high enough or was not applied long enough for the air in the smaller air voids to be completely dissolved, the number of voids per unit volume will remain almost unchanged even though the final air content could be a little lower than the initial value (if the dissolved air is not fully recovered). In such a case, the real spacing of air voids will be little modified, and thus the frost durability of concrete will not be significantly affected. However, if the pressure is sufficiently high or if this pressure is maintained for a sufficiently long period of time, it is likely that all the air voids having a diameter smaller than some critical value will be completely dissolved. In that case, the number of air voids per unit volume of concrete will be significantly reduced during pumping. When the pumping pressure is released, the dissolved air will mainly ingress into the existing voids (because this requires less energy than forming new air voids), and the small air voids that were completely dissolved during pumping will not be recovered. Consequently, the real spacing of the air voids will be significantly increased, and the frost durability of concrete will be reduced.

The mechanisms described, which are considered responsible for the loss of air during pumping, are supported by the test results presented. Even if the pumping pressures were not recorded at the job

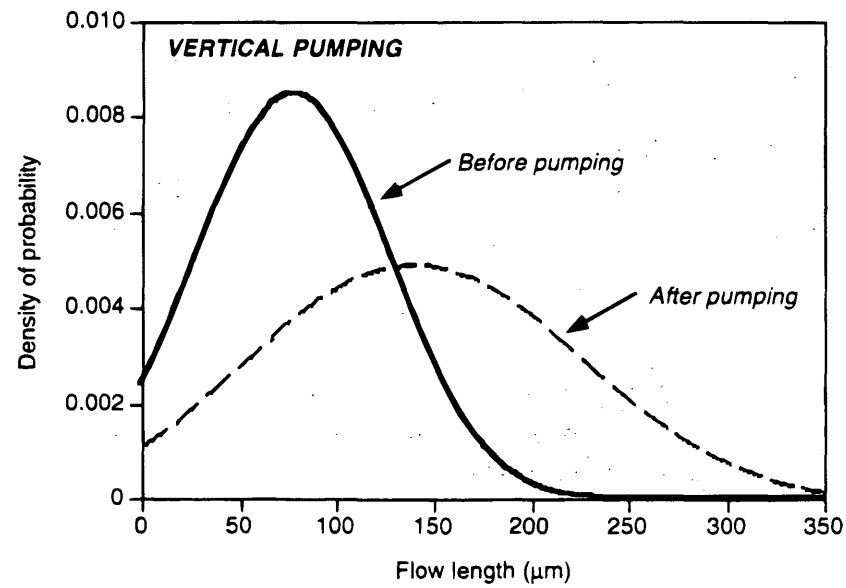

FIGURE 6 Statistical distributions of flow length obtained for specimens subjected to vertical pumping.

TABLE 3 Characteristics of the Air-Void System for Voids Having a Diameter Smaller than 300 μm as Obtained From Image Analysis

		Air Content (%)	Specific Surface (mm^{-1})	Spacing Factor (μm)	Number of Voids (nbr/cm^3)	Flow Length (μm)
Horizontal pumping	Before pumping	2.0	42.9	170	31 400	170
	After pumping	2.1	37.5	190	23 900	195
Vertical pumping	Before pumping	2.0	42.0	175	30 900	175
	After pumping	1.1	40.0	235	13 500	305

site, it is clear that the vertical pumping of concrete requires a higher pressure than horizontal pumping. It appears that, when the concrete was pumped horizontally, the pressure was not high enough to completely dissolve the smaller air voids (see Figure 3). Thus, the characteristics of the air-void system were little modified (see Figure 5 and Table 3), and the frost durability was not significantly influenced. However, when the same concrete was pumped vertically, almost all the air voids having a diameter smaller than 50 μm completely disappeared (see Figure 4). Even if the corresponding air loss was relatively small (0.9 percent according to Table 3), the number of voids per unit volume of concrete decreased dramatically (see Table 3), and the real spacing of the air voids increased significantly (see Figure 6 and Table 3). This increase is detrimental to the frost resistance.

A recent laboratory study by Elkey et al. (*4*) corroborates these findings. It was found that the pumping of concrete lowers the total air content, increases the spacing factor, and, most important, yields a coarser void-size distribution (as obtained by recording the chords intercepted according to the ASTM C 457 linear traverse method). It was also found that the differences were more important when the pumping pressure was increased or the pressure was applied for a longer time. Finally, it was observed that concretes having a higher initial air content are less detrimentally influenced by pumping, which is consistent with the mechanism described (if concrete initially contains more small voids, a higher pressure or a longer period of time, or both, will be required to completely dissolve them).

It is obvious from the data presented that the measurement of the air content alone cannot provide a good assessment of the influence of pumping on the quality of the air-void system. It is also clear, considering the data in Tables 2 and 3, that even the microscopical determination of the characteristics of the air-void system in hardened concrete according to ASTM C 457 (although it generally yields significant data concerning the frost resistance) cannot provide a precise assessment of the influence of pumping on the quality of the air-void system. Table 2 indicates that when concrete was subjected to either horizontal or vertical pumping, the spacing factor increased by approximately 60 μm, which represents an increase of roughly 33 percent in both cases. Table 3 indicates, however, that the flow length (which is a better estimate of the real spacing of the air voids) increased only from 170 to 195 μm in the case of horizontal pumping, but from 175 to 305 μm in the case of vertical pumping (i.e., an increase of approximately 75 percent). The simplifying assumptions underlying the ASTM C 457 method are such that the large voids (those larger than 200 or 300 μm) have an exaggerated influence on the test results. The spacing factor is thus less sensitive to the disappearance of the small voids than to the disappearance of the larger ones.

CONCLUSIONS

The results presented in this paper, which are based on tests performed on HPC, indicate that it is possible to explain the influence of pumping on the characteristics of the air-void system in terms of simple physical concepts. The detrimental influence of pumping is due to the dissolution of the smaller air voids in the mixing water and is a function of the pressure. It is also a function of the length of time during which this pressure is applied (*4*). The results further show that the ASTM C 457 method is not sufficiently precise to assess correctly the influence of pumping. More research is needed to determine the influence of the mixture composition (normal concrete versus HPC) and the air-entraining agent and to determine the relationships among the pressure, the length of time during which it is applied, the concrete properties, and the loss of the small air voids.

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