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Some findings on the usefulness of image analysis for determining the characteristics of the air-void system on hardened concrete

Richard Pleau *, Michel Pigeon, Jean-Luc Laurencot

Centre de Recherche Interuniversitaire sur le Béton (CRIB), Laval University, Québec, Canada G1K 7P4

Abstract

This paper discusses the usefulness of image analysis techniques in order to assess the characteristics of the air-void system in concrete. Test results indicate that such a technique can correctly assess the air-void characteristics as defined in ASTM C 457 Standard test method. However, the accuracy of the test results is not significantly improved as compared with the manual technique and the image analysis method must be very carefully validated before being used as a routine procedure. Test results also indicate that the image analysis technique failed to correctly assess the size-distribution of air voids and, for that reason, this technique cannot be used to provide a better estimate of the real spacing of air voids than the commonly used ASTM C 457 spacing factor.

Keywords: Image analysis; Air-void system; Air content; Specific surface; Spacing factor; Flow length; Frost resistance; Microscopic examination

1. Introduction

Since the pioneer work by Powers [1], air-entrainment has been commonly used to protect concrete against frost action and scaling due to freezing in the presence of deicer salts. During freezing, part of the water is forced out of the capillary pores to the nearest air void where it can freeze and thus restore the thermodynamic equilibrium. According to Darcy's law, this forced flow of water gives rise to disruptive pressures in the concrete because the permeability of the cement paste is very low. The efficiency of the air-void system created by air-entrainment is governed by the spacing of the voids which determines the maximum distance that unstable water must travel to reach an escape boundary (the disruptive pressures are proportional to the cubic value of this distance). The spacing factor, noted $\overline{L}$, is defined as half the average distance between the outer boundaries of two adjacent air voids. It can be obtained from a microscopic examination of hardened concrete according to the ASTM C 457 Standard test method [2]. There is strong experimental evidence that the spacing of the voids is the key factor governing the frost resistance of concrete. For ordinary concretes, it is generally accepted that the spacing factor should not exceed 200 or 250 μm [3].

The microscopic determination of the air-void spacing factor is a tedious task and, for obvious reasons, this factor cannot serve as an acceptance criterion at the job site. On the contrary, air content is a very convenient parameter because it can be easily and quickly measured directly on the fresh concrete. Any concrete delivered at a job site can thus be rejected if it fails to meet the specified air content requirement. This is why, for simplicity and convenience reasons, most standards only prescribe the total air content (usually 5–8% for severe exposure conditions), assuming that the spacing factor is inversely proportional to the air content. Unfortunately, recent studies have shown that the correlation between air content and spacing factor is not very good, which means that a satisfactory air content does not guarantee an adequate spacing factor [3]. Fig. 1 shows the relationship between the spacing factor and the air content for more than 600 laboratory as well as field concrete mixtures. For an air content ranging from 5% to 8%, the spacing factor can vary from 75 μm (which is excellent) to 425 μm (which is fairly poor and far beyond the usual limit of 200–250 μm limit). According to the authors' experience, almost all field concretes showing a poor frost resistance have an unsatisfactory spacing factor, even though their air content is often within the specified limits.

* Corresponding author.

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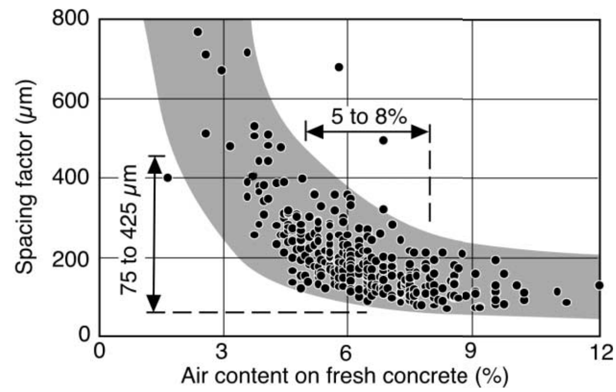

Fig. 1. Relationship between spacing factor and air content as obtained on more than 600 concrete mixtures made into the laboratory and at the job site.

The Canadian Standard CSA A23.1 [4] now sets a mandatory requirement on the value of the spacing factor ($\overline{L} \leqslant 230$ μm) for concretes subjected to severe exposure conditions. Most other standards and codes of practice set mandatory requirements on air content only, but it is generally recommended to keep the spacing factor below 200 or 250 μm. It is nevertheless true that the determination of the spacing factor raises concerns in all northern countries and that, with the recent availability of low-cost digitalizing boards and image analysis softwares on micro-computers, many attempts have been made to develop automatic systems to perform this task using image analysis techniques [5–11]. Such a system was developed at Laval University and this paper presents some findings concerning the usefulness of this system and of similar ones.

1.1. Why use image analysis?

The characteristics of the air-void system can be determined in three different ways as schematically illustrated in Fig. 2. The first method consists in recording the diameters of the circles intercepted by a plane passing through the volume of concrete. This is the method which is generally used with image analysis systems. The second method, the ASTM C 457 linear traverse method, consists in measuring the chords intercepted in the air voids along a series of regularly spaced lines of traverse. The third one, the ASTM C 457 modified point count method, consists in recording the frequency with which a series of points regularly spaced along the lines of traverse are superimposed on the air voids. For all three methods, it is possible to use the principles of stereology in order to compute the mean spacing of the air voids inside the volume of concrete. In the ASTM C 457 test method, the size-distribution of the air voids is not recorded because this task is considered too tedious to be performed manually. The spacing factor is thus computed assuming that all the air voids are equal in size and are regularly spaced in a cubic arrangement as shown in Fig. 3. These two simplifying assumptions are obviously not satisfied and, consequently, it can be demonstrated that the spacing factor only provides a rough index, which always overestimates the real spacing of the air voids.

What are the main reasons to use image analysis to determine the characteristics of the air-void system? The answer of this question is twofold. Firstly, image analysis can facilitate the work required by the ASTM C 457 test method, and also provide more reliable results, mainly because it eliminates the subjectivity of the operator which is very often perceived as a major drawback of ASTM C 457. Secondly, image analysis can contribute to a better assessment of the real spacing of the air voids in concrete by providing a simple and easy way to record their size distribution. This distribution cannot be easily obtained from the ASTM C 457 microscopic examination because the task is too tedious and time-consuming for the operator.

In recent years, different methods have been developed in order to mathematically reconstruct the spatial distribution of the air voids in concrete from the size-distribution of the voids intercepted by a plane or from the chords intercepted along lines of traverse [12–16]. In these methods, the only simplifying assumption is that air voids are randomly distributed throughout the volume of concrete and, for this reason, they provide a much better estimate of the real spacing of air voids than

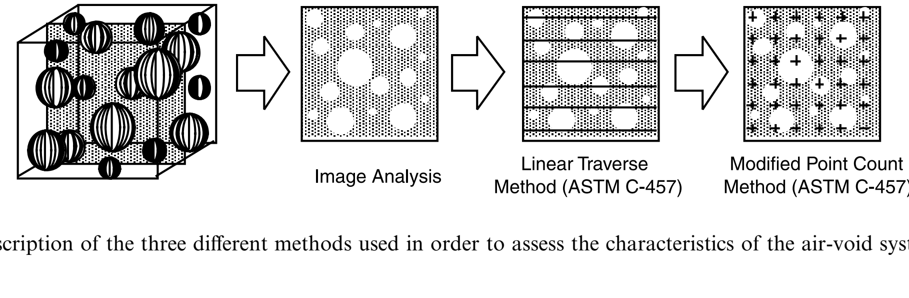

Fig. 2. Schematic description of the three different methods used in order to assess the characteristics of the air-void system in hardened concrete.

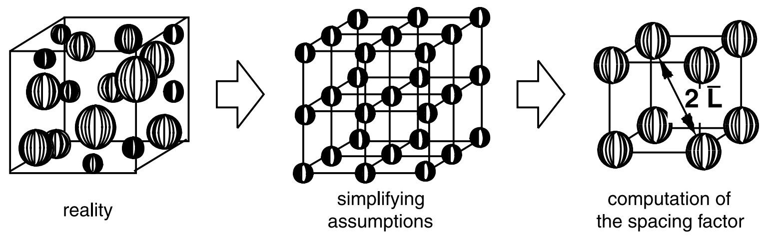

Fig. 3. Schematic description of the simplifying assumptions used in the computation of the ASTM C 457 spacing factor.

the ASTM C 457 spacing factor. At Laval University, such a method was developed in order to calculate the flow length value, noted Q_{98}, which is defined in such a way that 98% of the cement paste volume is located at a distance lower or equal to Q_{98} from the boundary of the nearest air void [12]. Physically, the flow length thus corresponds to the maximum distance that unstable water must travel during freezing. This index is quite similar to other ones (such as the Philleo factor or the protected paste concept) which were concurrently developed by other investigators. Results obtained from freezing and thawing tests clearly indicate that the flow length is a better indicator of the frost resistance of concrete than the spacing factor [13]. Fig. 4 shows that the relationship between the flow length and the spacing factor is quite scattered, which means that the determination of the spacing factor does not provide a good estimate of the flow length. There is no doubt that the availability of a reliable method which could easily be used to assess the flow length of the air-void system would represent a significant improvement for the control of the frost durability of concrete.

1.2. Image analysis test set-up used at Laval University

The image analysis test set-up developed at Laval University [17,18] is schematically described in Fig. 5. A

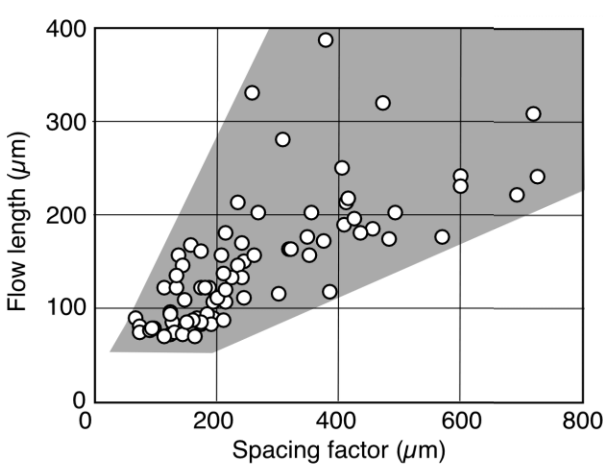

Fig. 4. Relationship between the flow length and the spacing factor.

$100 \times 100 \times 20$ mm^3 concrete specimen is placed on a motor-driven platform moving along two orthogonal directions. An optical microscope is fixed over the moving platform and the concrete surface is illuminated by a halogen lighting source passing through the optical path. A black and white CCD camera is mounted over the microscope and connected to a digitalizing board placed inside a PC-compatible micro-computer. Three electrical motors are installed on the set-up: the first two control the displacement of the moving platform and the last one controls the micrometric focus adjustment device of the microscope. The motors are driven by software developed specifically to provide an entirely automated measuring process.

Prior to the microscopic examination, the concrete surface is very carefully lapped using successively finer silicon-carbide abrasives in order to obtain a plane surface on which the boundaries of the air voids and of the aggregate particles are sharp and easily discernible. The voids are then filled with white ink under a vacuum device, and the concrete surface is wiped carefully with an alcohol-impregnated soft cloth to remove the excess ink. All voids thus appear perfectly white, or nearly so, while the remaining area is unaltered (i.e. cement paste and aggregate particles are clearly visible). The quality of the surface treatment is of paramount importance because any surface defect can be mistaken for an air void and can thus become a significant source of error. Only the concrete specimens with an excellent quality surface are subjected to the image analysis measurements.

Essentially, the test method consists in detecting the air voids on a number of images taken from the same concrete specimen, measuring the diameter of these voids and classifying them in a frequency histogram divided in class intervals. A difficulty arises from the fact that the diameter of air voids ranges from about 10 μm to more than 1 mm which represents a difference of two orders of magnitude. Under such circumstances, it is not possible to detect all the voids seen on a 512×480 pixel image. This problem was solved by taking two series of measurements at different magnification levels. In the first series (100×), a pixel represents 1.7 μm and each image thus covers a 0.71 mm^2 area (870×816 μm). At

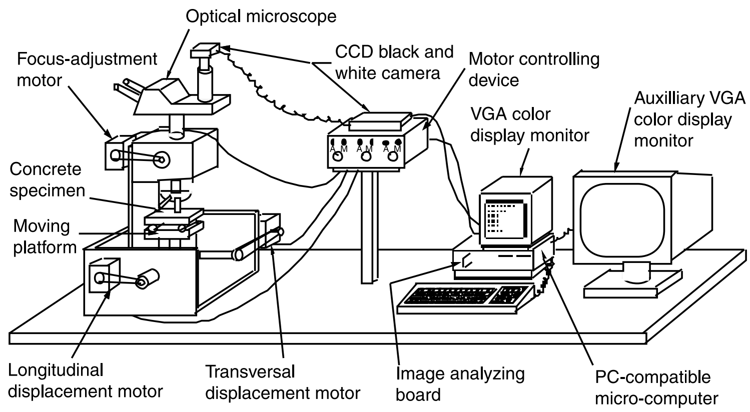

Fig. 5. Schematic description of the image analysis set-up.

this magnification level, a 10 μm air void roughly represents a 6 × 6 pixel area, and it was decided to record only the voids with a diameter ranging from 10 to 300 μm. A total of 400 images are examined, which represents a total area of 2.84 cm^2. The diameters of the air voids are recorded and classified in a 20 μm class interval frequency histogram. The number of voids recorded varies from about 150 (for non-air-entrained concretes), to more than 3000 (for air-entrained ones). In the second series (25×), a pixel represents 6.8 μm and each image covers a 11.36 mm^2 area (3.48 × 3.26 mm). At this magnification level, all the voids having a diameter larger than 300 μm, but smaller than 1 mm, are recorded and classified in a 50 μm class interval frequency histogram. A total of 50 images are examined, which represents a total area of 5.68 cm^2. The number of voids recorded ranges from 15 (for non-air-entrained concretes) to more than 100 (for air-entrained ones). For both series of measurements, the images are evenly distributed over a 75 cm^2 surface area in order to avoid, as much as possible, the variations due to the heterogeneity of concrete.

The frequency histogram is obtained by using the algorithm described in Fig. 6. To provide reliable results, this algorithm was designed to discriminate the air voids from surface defects, which are, unfortunately, unavoidable. This is mainly achieved by using a shape factor [17], which takes advantage of the spherical shape of air voids. After many trials, it was found that a combination of two shape factors gave the best results based on the judgment of a very experienced operator who visually identified and classified air voids and surface defects. It was thus decided that any object having a perimeter larger than 1.5 times the perimeter of a circle having the same surface area would be considered as a surface defect. Any object for which the ratio between the maximum length and the minimum diameter is larger than 2 is also considered as a surface defect. The combined use of these two shape factors gives good results but, unfortunately, it fails to correctly resolve the problem of overlapping air voids. This problem arises when air voids are located so close together that they overlap each other. In such cases, the algorithm considers the overlapped air voids as a single air void, or as a surface defect, which, in both cases, is an incorrect assessment. The overlapping of air voids is negligible in low air content concretes, but may be significant in high air content concretes.

For obvious reasons, the shape factors are no longer valid for objects touching the boundaries of the image frame. This problem was resolved by counting only the air voids which are entirely located inside the image frame and by multiplying this number by a correction factor which takes into account the statistical probability that an air void would be intercepted by the boundaries of the image frame. This correction factor is given by the following relationship:

$$1 + \frac{(a+d)d}{(a-d)(b-d)}, \tag{1}$$

where a and b represent the width and the height of the image, and d represents the diameter of the air void. Eq. (1) clearly indicates that the correction factor decreases with the overall dimension of the image because the probability that an air void touches the boundaries of the image is correspondingly reduced. For similar reasons, this factor increases with the diameter of the air voids because larger voids have a higher probability of being intercepted by the boundaries of the image.

The paste content can be obtained by a simple binarization where the operator manually chooses the threshold which best discriminates the aggregates from the cement pastes on a series of 10 images taken at the smaller magnification level (25×). For dark aggregates having a uniform color, such as limestone, this procedure gives good results. However, a simple thresholding was found to be unsatisfactory when aggregates contain mineral constituents covering a wide range of gray lev-

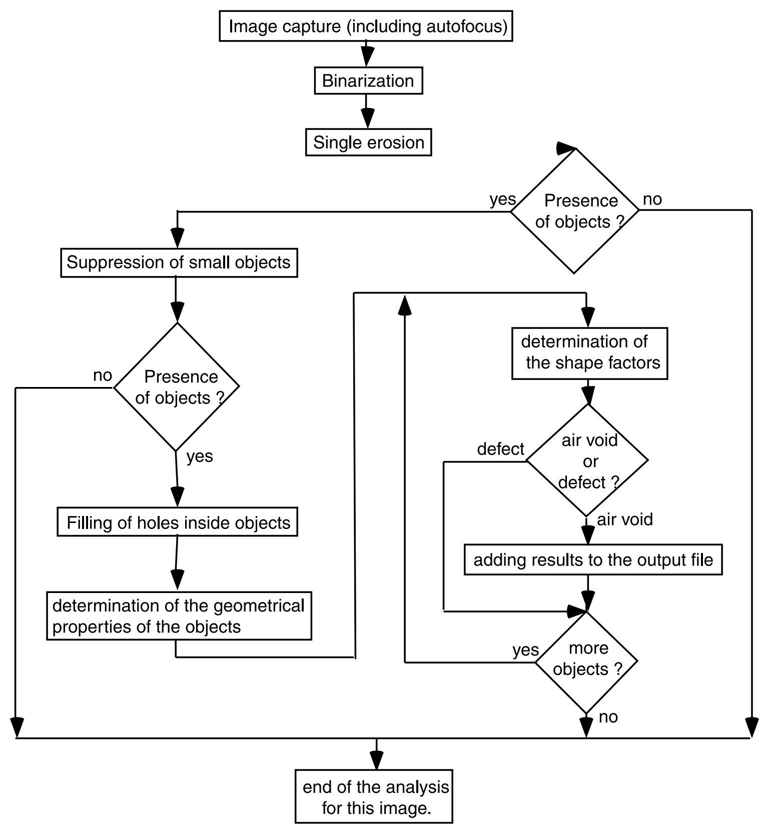

Fig. 6. Simplified algorithm of the resolving procedure used for each image examined.

els. In many cases, the paste content can however be estimated accurately enough from the known composition of the concrete mixture, when this information is available.

The test procedure is entirely controlled by computer and the treatment time for a complete analysis (i.e. $400 + 50$ images) is about 40 min, the limiting factor being the time required to mechanically move the platform.

1.3. Determination of the characteristics of the air-void system

Once the size distribution of the air voids has been obtained from image analysis, the main characteristics of the air-void system, i.e. the air content, the specific surface, and the spacing factor, can be easily computed according to the laws of stereology [18].

The air content (A) corresponds to the volume occupied by the air voids expressed as a percentage of the total volume of hardened concrete. It is given by the ratio of the surface occupied by the air voids to the total surface examined under the microscope. Thus

$$A = \frac{100}{S}\frac{\pi}{4}\sum_{i=1}^{n} n_i d_i^2, \tag{2}$$

where S is the total surface examined, n the number of classes in the frequency histogram, n_i the number of air voids contained in class i, and d_i is the mean diameter of the air voids in class i.

The specific surface of air voids (α) is defined as the ratio between the surface area of air voids and the total volume occupied by these voids. It can be obtained from the following relationship:

$$\alpha = \frac{16}{\pi}\frac{\sum_{i=1}^{n} n_i d_i}{\sum_{i=1}^{n} n_i d_i^2}. \tag{3}$$

According to the definition of the ASTM C 457 Standard test method, the spacing factor ($\overline{L}$) is given by the following relationships:

$$\overline{L} = \frac{PS}{4\sum_{i=1}^{n} n_i d_i}, \quad \text{when } P/A \leqslant 4.34, \tag{4}$$

$$\overline{L} = \frac{3}{\alpha}\left[1.4\left(\frac{P}{A}+1\right)^{1/3} - 1\right], \quad \text{when } P/A > 4.34, \tag{5}$$

where P represents the paste content expressed as a fraction of the total volume of concrete.

2. Test results

2.1. Comparison with the ASTM C 457 Standard test method

Figs. 7–9 compare the results obtained by the image analysis test method with those obtained from the ASTM C 457 Standard test method as regards the air content (Fig. 7), the specific surface of the air voids (Fig. 8), and the spacing factor (Fig. 9). The results reported in these figures were obtained for nine different concrete mixtures covering a wide range of air contents. The ASTM C 457 microscopic examinations were carried out by a very experienced operator in order to provide values as reliable as possible for comparison purposes.

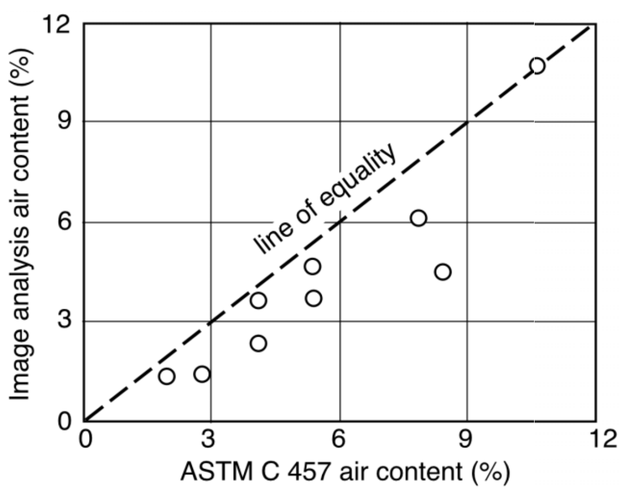

Fig. 7. Relationship between the air content determined by the image analysis method and the air content determined by the ASTM C 457 microscopic examination.

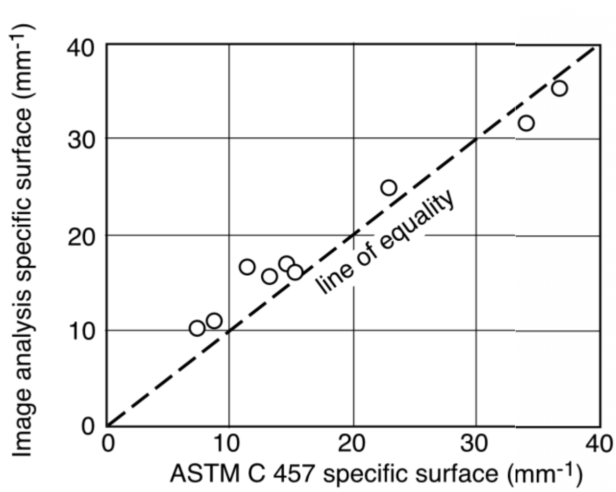

Fig. 8. Relationship between the specific surface of air voids determined by the image analysis method and the specific surface of air voids determined by the ASTM C 457 microscopic examination.

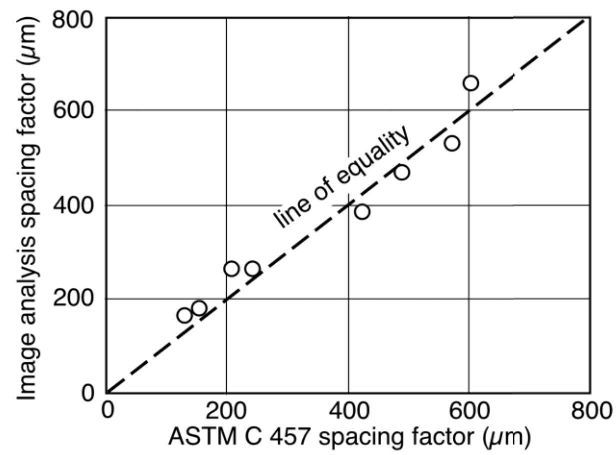

Fig. 9. Relationship between the spacing factor determined by the image analysis method and the spacing factor determined by the ASTM C 457 microscopic examination.

Fig. 7 first indicates that the image analysis method always underestimates the total air content of concrete. The error is significant because the air content obtained from image analysis is, in average, 30% smaller than the air content obtained from the ASTM C 457 microscopic examination. This large difference is certainly due, to some extent, to the fact that all the air voids are taken into account in the ASTM C 457 method while the image analysis system is restricted to voids for which the circle intercepted by the observed plane is smaller than 1 mm. The difference is significant because voids larger than 1 mm occupy a large volume even though they represent a negligible percentage of the total number of voids observed on the surface. The difference between image analysis and ASTM C 457 Standard test method is also most probably due, to some extent, to the fact that certain large air voids are considered as surface defects by the image analysis system. This error of interpretation is most likely to occur when the quality of the surface treatment of the concrete specimen is unsatisfactory, or when air voids overlap each other which, according to the author's experience, is not uncommon.

Fig. 8 shows that the correlation between the specific surface of the air voids obtained from image analysis, and that obtained from the ASTM C 457 Standard test method is much better than the correlation observed for air content. The image analysis system generally overestimates the specific surface, but the average error is approximately equal to 20%, which is quite similar to the variability associated with the ASTM C 457 test method.

Fig. 9 shows an even better correlation between the two methods when the spacing factor is considered. The points on this figure are very close to the line of equality and the average difference between the values obtained from these two methods does not exceed 8%, which is comfortably within the variability associated with the ASTM C 457 Standard test method.

From the results reported in Figs. 7–9, it could be concluded that the image analysis system developed at Laval University correctly assesses the specific surface of the air voids and the spacing factor, but that it underestimates the air content. It is important to note, however, that these mixtures were made with limestone aggregates having a dark and uniform color, which contrasts sharply with the surrounding cement paste. For other types of aggregates, especially those having a pale color or containing different mineral constituents, the differentiation between air voids, cement paste, and aggregates is more difficult to perform by the image analysis algorithm, which can yield a significant error on the computation of the characteristics of the air-void system. This problem could be avoided by impregnating the concrete surface with black ink prior to filling the voids with white ink in order to produce an almost binary image prior to the microscopic examination [6]. But the surface treatment is thus more tedious and difficult to carry out, and the paste content cannot then be obtained by image analysis.

It was also found that the quality of the surface treatment is of paramount importance, and that the quality standards must be fixed at a much higher level for the image analysis system than for the ASTM C 457 visual examination. A concrete surface can be considered inapt to be subjected to the image analysis test method, although it is otherwise considered satisfactory according to the ASTM C 457 Standard test method requirements. This is essentially due to the fact that the human eye is more qualified to separate the air voids from surface defects than the computer. The importance of the surface treatment is also amplified by the ink filling process which can contribute to produce surface defects if the voids are not completely filled with ink or if the surface is not wiped sufficiently to remove all the excess ink.

For all these reasons, the comparison of the results obtained with the image analysis method and the ASTM C 457 test method is not always as good as it appears in Fig. 7. In the authors' point of view, a strong validation process must be carried out on a large number of different concrete mixtures before any image analysis method can be used as a routine procedure in lieu of the ASTM C 457 visual examination method.

2.2. Use of image analysis to better estimate the real spacing of air voids in concrete

The use of image analysis can also be used to compute the flow length value (Q_{98}), or any other similar parameter such as the Philleo factor or the protected paste concept. As mentioned earlier, the flow length is a much better index of the real spacing of air voids in concrete than the ASTM C 457 spacing factor. However, in order to compute the flow length with a satisfactory precision, it is mandatory to properly estimate the size distribution of the air voids. This size distribution is mathematically deduced from the frequency histogram of the diameter of the air void circles which are intercepted by the concrete surface observed under the microscope.

Figs. 10 and 11 show the frequency histograms measured on two of the concrete mixtures from Figs. 7–9. These frequency histograms are quite typical of those obtained for many other concrete mixtures tested in our

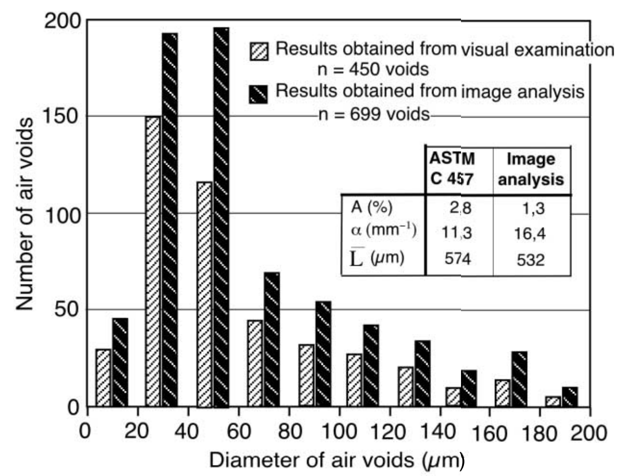

Fig. 10. Typical example of the frequency histogram of the diameter of air-void circles seen on the examined concrete surface as obtained from image analysis and visual examination for a non-air-entrained concrete.

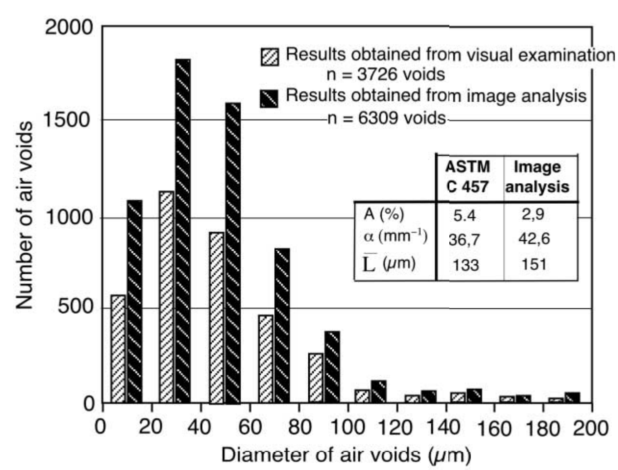

Fig. 11. Typical example of the frequency histogram of the diameter of air-void circles seen on the examined concrete surface as obtained from image analysis and visual examination for an air-entrained concrete.

laboratory and elsewhere. Figs. 10 and 11 compare the frequency histograms obtained from the image analysis system with the frequency histograms obtained by a very experienced operator who manually measured and recorded the diameter of the voids directly on the computer screen for the same series of images. Figs. 10 and 11 only show the frequency histograms obtained at the high magnification level (100×), because voids larger than 300 μm in diameter only account for a negligible fraction of the total number of voids even though they represent a significant fraction of the total air content. While examining Figs. 10 and 11, one can first notice that the frequency histograms are quite narrow with a sharp peak at 30 μm. Previous work on a large number of different concrete mixtures has clearly shown that this shape is very typical [8,12,19,20], and that it can be considered as an intrinsic property of the air-void system in normal fluid concrete, irrespective of the mixture composition or of the nature of the air-entraining agent or of the use of any other admixture.

Figs. 10 and 11 clearly indicate that the image analysis test method significantly overestimates the total number of air voids, although the shape of its frequency histogram is quite similar to the histogram obtained from the visual examination. This overestimation is particularly important for air voids smaller than 80 μm in diameter. In fact, the number of air voids recorded by the image analysis test method is generally 50–70% higher than the number of voids recorded by the visual examination, which represents a very significant difference. The flow length values are not reported here, but it is clear that the frequency histograms obtained from the image analysis test method would lead to significantly underestimate the flow length because this parameter is closely related to the total number of air voids seen on a unit surface area. The overestimation of the number of air voids by the image analysis test method is most likely due to the fact that, in the 0–80 μm class interval, the algorithm is unable to correctly discriminate air voids from surface defects or other artefacts such as minute color changes in the cement paste. The overestimation of the number of air voids could possibly be reduced, to a limited extent, by improving the surface treatment process of the concrete specimens.

It is quite surprising that the image analysis test method provides a very good estimate of the spacing factor even though it greatly overestimates the number of air voids contained into a unit volume of concrete. This apparent contradiction can be explained by the fact that the very small air voids have only a little influence on the computation of the specific surface of the air voids. According to Eq. (4), the specific surface is inversely proportional to $\sum_{i=1}^{n} n_i d_i^2$ which means that, for small void diameters, the term d_i^2 is very small and, consequently, the term $n_i d_i^2$ is also small, even though the number of voids (n_i) is high. Since the spacing factor is inversely proportional to the specific surface (Eq. (5)) or to $\sum_{i=1}^{n} n_i d_i$, it can also be concluded that the computation of the spacing factor is also only little influenced by the very small air voids which is, clearly, one of the major drawbacks of the ASTM C 457 test method. As seen earlier, the image analysis test method generally tends to underestimate the air content (and consequently underestimate the spacing factor), but to slightly overestimate the specific surface (and consequently overestimate the spacing factor). These two tendencies counteract one another, to some extent, to reduce the error made in the computation of the spacing factor.

It can thus be concluded that the image analysis test method would fail to correctly assess the flow length value, because most surface defects and other artefacts of the surface treatment technique (such as minute color changes) unfortunately fall in the same narrow size range (10–100 μm) as most of the entrained air voids. The development of a more efficient surface treatment technique and a significant refinement of the image analysis algorithm are therefore necessary before the image analysis test method developed at Laval University can be reliably used to assess the flow length. This is, however, a large task, and, in the authors' opinion, the results would not necessarily be very good.

2.3. Usefulness of the image analysis test method

Image analysis as a substituting method to visual examination in order to assess the characteristics of the air-void system as defined by the ASTM C 457 Standard.

The first reason for which it could be advantageous to use an image analysis test method is to provide an easier and more reliable method to assess the parameters of the air-void system as defined in the ASTM C 457 Standard (air content, specific surface, and spacing factor). It is generally believed that a method based on image analysis is easier than the ASTM C 457 microscopic examination because all the measurements are made by the computer instead of a human being. It is also believed that such a method provides more reliable results because they are not influenced by the subjectivity of the operator. The test results reported here confirm that an image analysis method can correctly assess the spacing of the air voids and the other characteristics of the air-void system. Nevertheless, the usefulness of image analysis for that purpose is questionable for the reasons described below.

Recent study at Laval University has shown that, provided that the statistical sampling is large enough, the ASTM C 457 modified point count method is as good and accurate as the linear traverse method, although it is much more rapid and easy to carry out [21]. This explains why, at least in Canada, this method is by far the most widely used. The vast experience acquired at Laval University during the last 20 years indicates that, for each air-void characteristic measurement, the surface treatment of the concrete specimens takes roughly 45 min and the microscopic examination between 60 and 120 min. In the authors' point of view, the use of an image analysis system will not reduce the time required for the measurement, especially considering the fact that image analysis requires a much better surface treatment, which is quite time-consuming. Considering the cost of the image analysis set-up, the use of image analysis is probably not worth the investment, unless the determination of the air-void system characteristics becomes very common and the number of tests carried out each year thus very high.

Contrary to common belief, the variability associated with the ASTM C 457 microscopic examination is quite acceptable, provided that the examination is carried out properly by a well-trained operator [22]. For example, the maximum error expected on the spacing factor is approximately equal to 15% (this value includes the variability associated with the subjectivity of the operator), which is quite satisfactory. This means, for example, that if a concrete producer adopts a 200 μm maximum (target) value for the spacing factor, he should normally meet the requirements of the CSA A23.1 Canadian Standard ($\bar{L} \leqslant 230$ μm). A round-robin test study carried out with the participation of a dozen different laboratories throughout Eastern Canada has recently confirmed that the variability of the ASTM C 457 Standard test procedure is quite satisfactory [23]. This study also highlighted the fact that the subjectivity of the operator is not a very important source of variability, provided that the operators are carefully trained by an experienced instructor. For all these reasons, it is considered that the accuracy of the ASTM C 457 Standard test method would not be very significantly improved by the use of an image analysis method.

2.4. Image analysis as a mean to better assess the efficiency of the air-void system in concrete

The second reason for which it could be advantageous to use an image analysis test method is to compute the flow length value, or any other similar index, which corresponds to the maximum distance that freezable water must travel to reach the outer boundary of the nearest air void. As demonstrated elsewhere, the flow length is much more efficient than the commonly used ASTM C 457 spacing factor (which is only a rough estimate of the mean spacing of air voids) to assess the frost resistance of concrete. This index would be especially useful for the new generation of high-performance concretes which are generally more frost resistant than ordinary concretes. The flow length would be also very useful to assess the influence of different parameters on the air-void system. For example, a recent study has shown that the flow length is much more sensitive than the spacing factor to assess the detrimental influence of pumping on the air-void system of certain high-performance concretes [24]. For these reasons, it is clear that an image analysis automatically computing the flow length would be a very significant improvement in the field of concrete frost durability.

The test results described indicate that the image analysis test method failed to correctly assess the size distribution of the air voids. Although the shape of the frequency histogram is correct, this method overestimates by about 70% the number of voids seen on the examined surface. Of course, this overestimation also yields to overestimate the number of voids per unit volume of concrete and, consequently, to underestimate the flow length. Thus, the flow length obtained from the image analysis system described is clearly not reliable enough to be used as a durability index.

The major drawback of the image analysis method is to greatly overestimate the number of voids in the 10–90 μm diameter range. This overestimation can be explained in three different ways:

1. The surface defects and variations in color are essentially concentrated in this size range.
2. The distinction between air voids and surface defects in this size range is not clear-cut, and it is very difficult to define simple rules which could be incorporated into an algorithm, and be efficient for a wide range of conditions.
3. For air-entrained concretes, overlapping of air voids is quite common in this size-range. The separation of overlapping air voids is relatively easy for the human eye, but very difficult to achieve by image analysis (all the algorithms tried at Laval University gave poor results in this respect).

Unfortunately, there is no easy way to eliminate, or significantly reduce, the inability of image analysis to correctly assess the size distribution of air voids. Furthermore, in order to become a useful durability index, such as the ASTM C 457 spacing factor, the flow length would need to be easily measurable by a relatively large number of laboratories. This could be achieved only if a low-cost and reliable image analysis system would be readily available on the market and if, at the same time, the surface treatment of concrete specimens and the microscopic examination procedure would be precisely defined in a Standard.

3. Conclusion

The test results presented indicate that an image analysis method can be used to correctly assess the characteristics of the air-void system defined in the ASTM C 457 Standard test method. However, such a method has to be very carefully validated before being used as a routine procedure. The validation process must necessarily include comparisons between the values obtained from image analysis and those from the ASTM C 457 visual examinations for a large number of concrete mixtures covering a wide range of mixture compositions and air contents. The quality of the surface treatment of concrete specimens prior to the microscopic examination appears to be a key factor, and this topic would probably require future investigation.

Notwithstanding the obvious advantages associated with image analysis, this method is not expected to increase significantly the accuracy or the reliability of the test results as compared with the ASTM C 457 Standard visual examination. Furthermore, the image analysis method would most probably not significantly reduce the cost associated with the measurement, or the time required.

Unfortunately, the image analysis system developed failed to satisfactorily assess the size distribution of the air voids and, for that reason, cannot be used to provide a better index of the efficiency of the air-void system than the ASTM C 457 spacing factor.

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