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A quantitative measurement of concrete air content using image analyses

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Abstract. A proposed topology method is introduced to measure the air content of fresh cement paste and hardened concrete. The method takes advantage of chromatographic analysis in void areas that are highlighted using different color schemes and later calculated using built-in computer software. The air content measured by the topology method is compared with results obtained from the conventional ASTM methods. It is concluded that the proposed method is reliable, and costs less and is easier to operate compared with the ASTM methods. In addition, 3 dimensional pore models can be created using image post-processing techniques. The proposed method helps researchers in understanding the formation and existence of concrete pores. This paper reports a detailed test program demonstrating the standard operating procedure used for the proposed method and presents a comparison of results between the proposed method and conventional ASTM Specifications. It is also concluded that the air content increases with increasing size of pores and increasing percentage of coarse aggregates.

Keywords: air content; topology method; image analysis.

1. Introduction

There are several methods to quantify the porosity ratio and void distribution in fresh and hardened concrete. (Werner *et al.* 1999) applied a grey-level threshold technique in image analysis to measure air bubbles of hardened concrete. The results were found correlated comparing with the results obtained using ASTM C173 (volumetric method), ASTM C185 (weighing method), and ASTM C231 (pressure method). The volumetric method is a direct method, collecting and measuring the entrapped air bubbles of fresh concrete before complete hydration occurs. The Pressure Method is an indirect method. It indicates the concrete air content in terms of the pump pressure that transformed by the use of Boyal's Law. Both the direct and indirect method generates similar results for the porosity ratio in fresh concrete.

The Mercury Intrusion Porosimetry (MIP) method is usually used to measure capillary pores sizes between 120 μm to 3 nm in hardened concrete (Gallie 2001). Mercury is first forced into the

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concrete pores and the piezoelectricity change is traced, becoming an indicator to calculate the pore quantity, as reported by (Wong *et al*. 2006, Werner *et al.* 1999). The procedure is complex and costly, and the error existing in the data shows 10-100 times discrepancies from the actual pore sizes, as concluded by (Diamond 2000). The error is eliminated using a direct approach as directed in ASTM C457 by using the section-analysis method. (Aligizaki *et al*. 1999) and his research associates use an Optical Microscope (OM) technique to measure cumulative blowhole quantities with promising results a system of round robin method for hardened concrete, (Jana 1999). However, the image process requires a high-power (50 to 125 times) microscope making the measuring process lengthy and difficult.

The pressurized method is commonly used to determine the in-situ air content of fresh concrete. It is an excellent tool in determining macro pores and air void content. For pore size classification, (Chan *et al.* 2000) proposed 4 different size categories and suggested that the measuring technique should be size-specific. This paper proposes a new technique using digital camera (DC) images taken with a digital camera from treated concrete surfaces to quantify the total void content of both fresh air and hardened cement paste. The image obtained after the post-processing demonstrates consistent results compared with other means of measurement. It is a direct, easy-to-use concrete air content measuring technique.

2. Test programs

To develop an improved test scheme and to understand the characteristics of the proposed test method, two sets of concrete specimens are prepared.

2.1 Hardened concrete test specimen

The test specimens are made using Portland Cement Type I and standard sand in compliance with ASTM C778, grade 20-30. The coarse aggregates are machine-made gravel with specific gravity of 2.63. The concrete mix design conforms to ASTM C39. Three different mix designs are used in the test program, varying the water/cement ratio from 0.4 to 0.89. The fluidity of mortar is controlled within 100±10% and the concrete slump is kept between 5 cm to 15 cm. The 10 cm diameter column molds are filled with 3 pours using moderate vibration. The molds are detached within 24-hr and specimens are cured immediately after demolding. The mix designs of the specimens are expressed in their volumetric values and the material properties of the specimens are shown in Table 1 and 2, respectively.

Table 1 Concrete specimen mix design unit: kg

	w/c	Cement	Sand	Coarse
Mortar 1:1	0.35	3.5	14	-
Mortar 1:2	0.4	3.5	14	-
Mortar 1:4	0.74	3.5	14	-
Concrete 1: 1:1	0.39	8	8	8
Concrete 1: 2:2	0.62	4	8	8
Concrete 1: 4:4	0.89	2	8	8

Table 2 Mechanical properties of mix ingredients

	Cement	Sand	Coarse
Specific gravity	3.15	2.61	2.63
Specific area(cm^2/g)	3300	-	-
Fineness modulus	-	3.1	6.0
Absorption (%)	-	5.0	3.0

2.2 Measuring the air content in fresh concretes

Three kinds of air content tests are conducted at the same time for comparison. The first test is a weighting method, filling up a 400 ml vessel with 3 layers of material and compacting each layer 20 times according to ASTM C185. The weights of the specimens are measured and recorded after leveling. The second test, ASTM C173, is performed by filling 15 cm diameter vessels with 2 layers of cement paste and compacting each layer 25 times. Tap the vessel 5 times on the side and inject water into it by a long funnel. Invert the vessel once the surface water becomes still. Resulting air bubbles are released and ethyl alcohol is added. The total air content is equal to the total volume of ethyl alcohol added. Finally, the ASTM C231 method involves filling a 7 liter vessel with 2 layers of fresh concrete and compacting each layer 25 times. Pressure is pumped into the sample while tapping the vessel from the side. The pressure is converted into air content through the use of Boyal's Law.

2.3 Surface treatment

The hardened concrete sample surfaces are polished using a BETA polisher. After grinding, the supercleaner with supersonic action is used to remove powder residue that could block smaller pores after grinding. The supersonic wave used in the test program is DG-1 model with a shaking frequency of nearly 7,000 cycles per minute. It is concluded that the use a relatively thin sand paper (1 μm) provides a better specimen surface smoothness.

2.4 Image analyses

Advanced cameras are commercially available to photograph the concrete specimen. Generally, no specialized skills are required. Detail parameters and operating procedures are addressed in later sections of this paper.

2.4.1 Preparation for digital camera

The SONY T70 digital camera is used to photograph the concrete surface. The effective picture elements are 8 million pixels and the resolution is set to 96 dpi. The standard operational procedures for the image recording are as follows: (1) 2.5 cm thick concrete thin slices are cut by saw and prepared for surface treatment. (2) Use silica sand papers and 1 um thick diamond sand paper to grind the surface of test specimens. (3) Place paper clay on a flat surface, then press concrete slices against the paper clay. The topographic configuration of concrete void is obtained using a steady load of between 100-150 kg pressing the samples against the paper clay. (4) Adjust the stiffness of paper clay to produce the best results describing the blowhole shapes and void pattern. Apply dye at the paper clay surface to outline the void boundary for ease of distinction. (5) Take digital images under 150W halogen lights, adjusting the lighting to produce the best result.

2.4.2 Post processing images

The topographic cross section of hardened concrete air void as indicated on the paper clay can then be identified using a commercial program named Image Pro-Plus (IPP). The built-in automatic search function sets the grey-level threshold to filter out air holes from scanned surface images. The total area of void on the paper clay is calculated through the standard operating procedure as follows: (1) acquire images; (2) select Area of Interest (AOI); (3)set input parameters; (4)calibrate scale bars; (5) adjust brightness; (6) manually select scattered void as main objects; (7) perform computation; (8) select pseudo color function and save as a new file; and (9) repeat step (2)-(8) as required.

2.4.3 Building a 3D model for cement paste

3D models of cement paste void are constructed through connecting a series of images using a 7X optical stereomicroscope. The camera generates 30 pictures per second sizing 17.8 cm×17.8 cm with a resolution at 90 dpi. The air void image is taken varying the focal distance in the z-direction. The optical microscopic image is taken every 20 um at 1 um increment. Taking a 1 mm pore hole as an example, it usually takes about 50 pictures as the z value decreases from the bottom to the top surface of the pore. Through the built-in Image Pro Plus post-processing framework, a three dimensional void distribution and pore sizes can be illustrated using meshes or pseudo colors comparing numerical mercury porosimetry technique and the gallium intrusion technique (Kurumisawa *et al.* 2006, and Navi *et al.* 1999). The 150W halogen light facilitates the image selection process by making a distinction between holes boundary and solids. It is very helpful in constructing digital images from optical microscopes. The final output demonstrates the overall void quantity obtained from the data acquisition and 3D frame animation software.

A three dimensional image is constructed as follows: (1) Select “Open File” to activate images at all levels. (2) Select “Sequence” from the drop-down manual to merge files; (3) Input the frame scale of the image (the default units are set to be mm); (4) Select “3D Edit” to set up image spacing in the Z axis, detect values (a default value is set at 8), hypothesis smoothness index and the intensity (default value is set at 20)…etc.; (5) Setup image overlapping sequences; (6) Construct image using “Add All” and “Create” command. (7) Generate 3D graphs and outputs; (8) Perform in-depth analyses and statistical testing.

3. Quantitative results

Numerical results measuring the air content of the fresh concrete and hardened concrete using the proposed method are reported hereafter. The results are also compared with the air content measured using conventional measuring methods as described earlier. It is concluded that the proposed method generally shows good agreement and promising results with less cost and effort compared to conventional measuring methods.

3.1 Air content in fresh cement paste and green concrete mix

The air contents of new concrete and fresh cement paste are examined using the proposed method. The following paragraphs describe the detail and composition of the specimen and final observation.

3.1.1 Fresh cement paste

The fluidity of the cement paste under testing is 110-120% with water/cement ratio ranging from 0.35-0.74. All mixes are prepared and placed in 400 ml vessels. A slight bleeding is observed in most specimens. The air content is estimated by substituting the total weight of the mix into the formula. However, the formulae are only valid when considering cement paste. The air content of 1:1 and 1:2 mortars are also shown in Table 3. With a slight adjustment of the constants used in the formulae the results are close enough regardless of the measuring methods.

The stickiness of the gel affects the accuracy of air content measurement. The air contents are relatively easy to measure at a 1:4 ratio because sufficient friction exists between air bubbles and cement paste. It becomes harder as the ratio becomes lower. The bubble sticks to the cement paste making the air content estimate lower than that of the actual value from the volumetric method.

3.1.2 Green concrete mixes

The test results suggest that the air content measured by the pressure method is slightly higher than by the volumetric method when the water/cement ratio ranges from 0.39-0.89 and the slump is

Table 3 Air content measured using various methods

Methods / Mix types	w/c	C185-02 (%)	C173-07 (%)	C231-04 (%)	Image Analysis (%)
Mortar 1:1	0.35	2.3	3.0	3.1	2.8
Mortar 1:2	0.40	2.7	4.0	5.0	4.1
Mortar 1:4	0.74	3.6	5.0	5.6	5.1
Concrete (1:1:1)	0.39	-	1.3	1.5	1.0
Concrete (1:2:2)	0.62	-	1.8	1.9	1.4
Concrete (1:4:4)	0.89	-	3.0	3.2	2.3
Code Bias	-	1.6	No bias	No bias	-
Code Upper %	-	8~19	7	11	-

Table 4 Slump tests and unit weight of mix

	w/c	Fluidity (%)	Slump (cm)	Unit weight (kg/m^3)
Mortar 1:1	0.35	120	-	2156
Mortar 1:2	0.40	110	-	2205
Mortar 1:4	0.74	110	-	2088
Concrete (1:1:1)	0.39	-	10	2271
Concrete (1:2:2)	0.62	-	18	2281
Concrete (1:4:4)	0.89	-	5	2340

in between 5-18 cm. The air content is 3% by the volumetric method while it is 3.2% measured by the pressure method. More detail comparisons are shown in Table 3. Similar trends are observed with both the cement paste and green concrete mixes. In general, the air content of the green concrete mix is lower than that of the cement paste. It is believed that the air content increases with more coarse aggregate used in the concrete mix. The slump decreases with increasing cement-solid ratio as the unit weight increases from 2271 to 2340 kg/m^3, as shown in Table 4.

3.2 Air content in hardened concrete

Specimens are also prepared using the same mix design and concrete ingredients for measuring air content of hardened cement paste and concrete. The proposed topology method is used accompanying with image post process to accurately quantify air content. The following paragraphs describe the detail of preparation of the specimens and the final observations.

3.2.1 Hardened cement paste

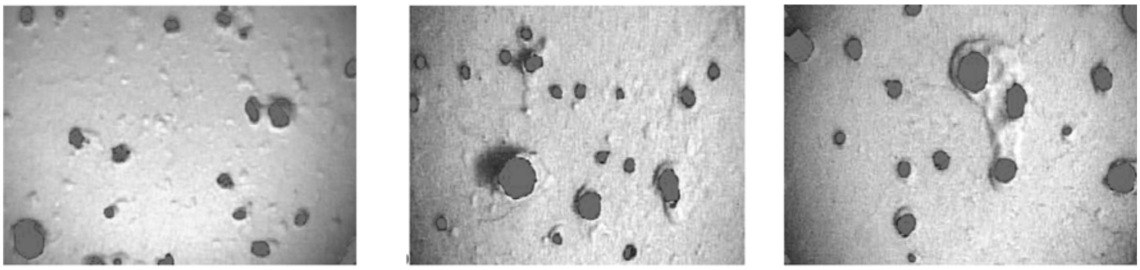
The hardened cement paste studied is cast in 2.54 cm diameter molds. The resolution of the 7x optical microscopic images covering the overall area of the test specimen is 90 dpi. The dying process under the topology method works well for distinguishing pore position and hole sizes. The computer software automatically selects and calculates the scattered void and air content, respectively. The results obtained using the topology method agrees with the results obtained from ASTM C173 and C231. The paper clay used in the topology method shows proper adhesion and the volumetric consistency remains less than 3%. The 45% water content paper clay is soft and neat. Its stickiness, flexibility and chemical stability are well suited for water color dying. It contains only non-toxic substances by the ASTM standard and a synchronous shrinkage during drying making the paper clay an excellent material in this application.

3.2.2 Hardened concrete mix

The topology method and procedure used for hardened concrete specimens is identical to what is used for the hardened cement paste samples except that a digital camera is used to take 10 cm×20 cm images. The overall process from creating paper topography, dying, taking photo images, and performing the computation for void content in the Image Pro Plus process takes only 15 minutes. The measurements are more time-consuming if conventional methods are used. Once the pore

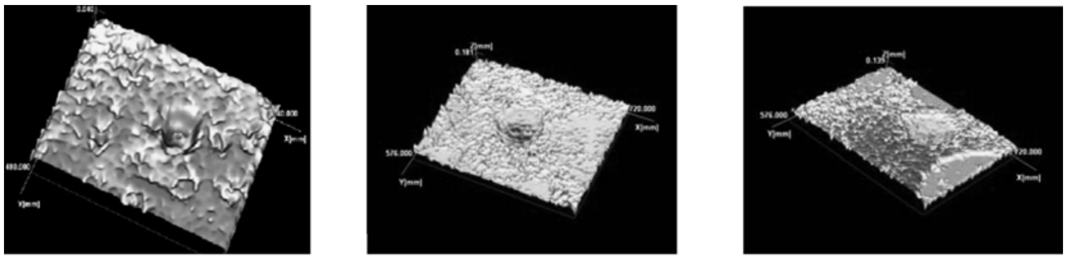
(a) (b) (c)

Fig. 1 Hardened concrete, cement and their void images: (a) Place concrete specimen underneath the compressor and force the paper clay into concrete surfaces, (b) The paper clay is oven dried after detached, (c) The protruding portions are colored



(a) (b) (c)

Fig. 2(a)~(c) Results from hardened concrete, cement and their void images analyses



(a)1:4 (b)1:2 (c)1:1

Fig. 3 Edited 3-dimensional images showing scattered voids in hardened cement paste

position is identified by the post-processor program, the overall air content estimates are straight-forward and accurate. Figs. 1(a), (b) and (c) shows typical samples and Figs. 2(a), (b) and (c) are views under from Image Pro Plus.

3.3 3D void distribution animation

A 3-dimensional void image can be constructed by overlapping 20 continuous images that are taken by a 50x microscope at 10 um increments in the z-axis. The air bubble sizes of 1:1, 1:2 and 1:4 ratio are 0.2 mm to 0.6 mm. Owing to 1.0×1.3 mm boundary limit of each image, the 3D void animation can only capture cement paste components that are less than 1 mm in sizes. A few scattered bubble images at media to microscopic levels are captured in Fig. 3.

4. Discussion

4.1 Topology method

A proposed method to acquire digital images of air bubbles from the cross sections of hardened cement paste or concrete in order to calculate the air content is introduced. The topology method requires a steady load of 100-150 kg to be applied at the interface of the test specimen and paper clay using a compressor to transfer the void configuration. The resulting impressions are highlighted using different color schemes. The total volume of the air bubbles at any given cross section is then calculated using built-in computer software recognizing the difference in colors between the pores and solid concrete surfaces. The proposed method is particularly useful for pore sizes between medium to large voids. Holes created by the concrete paste need special attention, requiring further research and are beyond the scope of this paper. In general, the proposed method is suitable and applicable for current practice. It is code compliant and manageable.

4.2 Setting up parameters

One of the important steps in obtaining successful output is setting up correct parameters. The input at "Area" is particularly critical in determining results. The initial area parameter used in the analyses is 10 unit/pixel. The search command is reset to be zero to ensure least error. In addition, the material background, texture, brightness, and filter sizes affect the quality of output images. It is preferred to use red pigment to give an outline of the air void in the relative grey concrete.

4.3 The quality of aggregates

The use of standard ASTM C778, Grade 20-30 well-graded sand in the test program helps to eliminate the potential effect of aggregate type. The quartz particles are easily seen using low-power microscopic lenses.

5. Conclusions

The topology method used for the air content measurement is less costly and less time-consuming, compared with conventional ASTM C457 methods. Its results generally agree with those of the ASTM methods. The proposed method is particularly suitable for medium to large pore sizes. A three dimensional pore distribution model of concrete pores can be constructed by overlapping several digital images taken at various depths. The air content increases with increasing size of pores and increasing percentage of coarse aggregates.

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References

Aligizaki, K.K. and Cady, P.D. (1999), "Air content and size distribution of air voids in hardened cement pastes using the section-analysis method", *Cement Concrete Res.*, **29**(2), 273-280.

Chan, Y.N., Luo, X. and Sun, W. (2000), "Compressive strength and pore structure of high-performance concrete after exposure to high temperature up to 800", *Cement Concrete Res.*, **30**(2), 247-251.

Chermant, J.L. (2001), "Why automatic image analysis? An introduction in this issue", *Cement Concrete Compos.*, **23**(2-3), 127-131.

Diamond, S. (2000), "Mercury porosimetry-an inappropriate method for the measurement of pore size distributions in cement-based materials", *Cement Concrete Res.*, **30**(10), 1517-1525.

Gallie, C. (2001), "Effect of drying on cement-based materials pore structure as identified by mercury intrusion porosimetry: a comparative study between oven-, vacuum-, and freezw-drying", *Cement Concrete Res.*, **31**(10), 1467-1477.
Jana, D. (2007), "A round robin test on measurements of air void parameter in hardened concrete by various automated image analyses and ASTM C457 methods", *Proceeding of the twenty-ninth conference on cement microscopy*, Quebec city, PQ, 34-69, Canada.
Kurumisawa, K. and Tanaka, K. (2006), "Three-dimensional visualization of pore structure in hardened cement paste by the gallium intrusion technique", *Cement Concrete Res.*, **36**(2), 330-336.
Navi, P. and Pignat, C. (1999), "Three-dimensional characterization of the pore structure of a simulated cement paste", *Cement Concrete Res*., **29**(4), 507-514.
Rattanasak, U. and Kendall, K. (2005), "Pore structure of cement/pozzolan composites by X-ray microtomography", *Cement Concrete Res.*, **35**(4), 637-640.
Sahu, S., Badger, S., Thaulow, N. and Lee, R.J. (2004), "Determination of water-cement ratio of hardened concrete by scanning electron microscopy", *Cement Concrete Compos.*, **26**(8), 987-992.
Soroushian, P. and Elzafraney, M. (2005), "Morphological operations, planar mathematical formulations and stereological interpretations for automated Image analysis of concrete microstructure", *Cement Concrete Res.*, **27**(7-8), 823-833.
Werner, A.M., Lange, D.A. and P.E. (1999), "Quantitative image analysis determination of masonry mortar microstructure", *J. Comput. Civil Eng.,* **13**(2), 110-115.
Wong, H.S., Head, M.K. and Buenfeld, N.R. (2006), "Pore segmentation of cement-based materials from backscattered electron images", *Cement Concrete Res.*, **36**(6), 1083-1090.
Yang, R. and Buenfeld, N.R. (2001), "Binary segmentation of aggregate in SEM image analysis of concrete", *Cement Concrete Res.*, **31**(3), 437-441.

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