- Technical Paper -

EVALUATION OF WATER ABSORPTION CHARACTERISTICS IN CONCRETES OF DIFFERENT STRENGTHS BY USING DIGITAL IMAGE CORRELATION METHOD (DICM)

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ABSTRACT

In this study, one-dimensional water absorption test was conducted along with DICM on small size oven dried concrete specimens of three different strengths. The changes of waterfront positions during the water absorption process and the progression of deformations in the saturated regions of mortar parts in concretes were clearly visualized in all specimens by utilizing DICM. The absorption characteristics determined from observations in DICM were related to the compressive properties and expansion strain in the same specimens.

Keywords: water absorption, strain generation, DICM, compressive strength

1. INTRODUCTION

Water absorption is a critical factor related to the durability deteriorations of concrete materials. Since as a carrier of the most aggressive ions, water directly or indirectly leads to durability related damages and performance degradations. So, in order to accurately predict the serviceable life of the concrete structures, it is very important to evaluate the water absorption distribution and understand its transport mechanism in concrete materials.

In the past researchers like [1] attempted to quantitatively evaluate and visualize the water absorption in cementitious materials by employing techniques like X-ray radiography, Nuclear Magnetic Resonance (NMR), and Electrical Resistance Tomography (ERT) etc. Many studies also perform gravimetric measurements according to ASTM C1585 [2]. Despite the limitations in accuracy of measurements for quantifying water absorption in concrete materials, these methods are laborious, time-consuming, sensitive to concrete qualities and demand special arrangements, and lack in providing information on possible deformations in concrete materials due to swelling in cement hydrates. However, in recent advancements, such as those by Igarashi et al. [3], [4], focused on the volumetric expansion of C-S-H due to water absorption and succeeded in visualizing the water penetration within the mortar during a water absorption test using image processing.

In this study, the authors extended the application of Digital Image Correlation Method (DICM) to determine characteristics like water absorption depth/rate and material deformability due to swelling in cement hydrates by performing one-dimensional water absorption test (without involving any influence of gravitational effects on absorption) on oven dried concrete thin slice specimens of three different compressive strengths. In addition to evaluating the water absorption characteristics, all the specimens were tested under compression to determine their compressive properties (i.e. compressive strength, f_c' and Young's modulus, E) to assess their relationships with the water absorption characteristics determined from observations in DICM.

2. EXPERIMENTAL OUTLINES

2.1 Materials and Mix Proportions

In this study, concretes of three different strengths (categorized as low, medium and high) based on different water to cement (W/C) ratios were prepared by using high early strength cement for low and medium strength concretes and Ordinary Portland Cement (OPC) for high strength concrete. Two types of chemical admixtures were used in preparing concrete mixes like air entrainment agent (AE) in low and medium quality concrete, and the superplasticizer (SSP-104) in high strength concrete. Table 1 shows the details of each mix proportion and correspondingly the compressive properties determined (after water absorption with DICM) at the age of 259,244 and 257 days in low, medium and high strengths respectively.

2.2 Test Specimens, their Conditioning and Preparation for Testing

At first prisms with dimensions 150 x 100 x 450 mm^3 were cast in steel formwork by considering three strengths based on different W/C ratios. All the concrete prisms were demolded after 24 hours and immediately placed under water for curing inside a control room; where temperature and humidity were maintained at 23

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Table 1 Mix proportions and compressive properties of concretes

Strength	W/C	G_{max} (mm)	S/a	Contents unite weights (kg/m^3)						f_c’	E
				W	C	S	G	AE	SSP-104	MPa	GPa
Low	0.65	20	0.63	295	454	1135	663	5.35	-	43.2	28.1
Medium	0.55	20	0.67	295	535	1339	663	5.35	-	54.5	29.6
High	0.30	15	0.41	165	555	709	1004	-	3.05	76.9	39.2

S/a; ratio of sand to total solids, W; water, C: cement, S; Sand, G; gravel aggregates

± 2 °C and 95 ± 5% respectively, for the complete curing duration. Later, these concrete prisms were cut into several thin slices (rectangular in shape) at the ages of 56, 58, and 57 days for low, medium, and high-strength concretes, respectively. These thin slices have dimensions L=150±1.7 mm, W= 100±3.5 mm and thickness = 50±5.5 mm in all cases. All the specimens of low, medium and high strength concretes were cured under water for 233, 222 and 232 days and subsequently tested for water absorption at the age of 243, 233 and 242 days, respectively.

The most widely adopted drying procedure for characterizing capillary absorption in concretes e.g. ASTM C1585 [2] suggests oven drying of specimens (i.e. 50 mm thick discs) at 50±2℃ for 3 days. However, in a study by Zhutovsky et al. [5] oven drying of specimens at 60℃ until gaining constant weight was found to be more appropriate with the assumption that rigorous drying could result in better correlation with transport properties in concrete materials. Similarly, in this study all the test specimens were oven dried at 60°C for 2 days with the assumption to obtain completely dried specimen.

After the oven drying each specimen was immediately wrapped in plastic sheet and kept in temperature and humidity control environment for a few hours to achieve a homogenized moisture condition in the whole specimen. Then plastic sheet was removed, and all surfaces of the specimen were sealed by applying silicon except one longer side/edge (to allow water penetration) and the top face (to be used for DICM), as illustrated in Fig.1. A masking tape was applied on the side and top face to avoid traces of silicon while its application on other sides to seal against water. On next day, before applying surface strain gauges over on DIC face masking tape was cut at designated points for attaching gauges and the remaining surface was saved from dispersion of adhesive used to attach the gauges. As indicated in Fig.1 the face for DICM was divided into

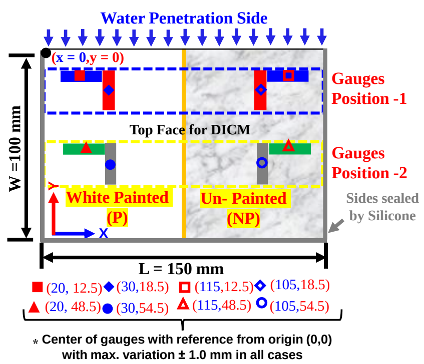

Fig. 1 Plane (xy) view of the test specimen with nominal dimensions showing positioning of gauges on face for DICM

two halves i.e., Painted side (P) and Un-Painted side (NP) over which eight general-purpose surface strain gauges were attached. Moreover, the arrangement of gauges was kept identical on both the halves in x/y-axis with respect to the direction of water penetration.

After attachment of surface strain gauges the specimens were placed in a glass chamber under constant temperature and humidity for ~24 hours and then half face was coated with matte type white paint to decrease the influence of color change and to achieve good quality speckles for DICM. Then the specimen was returned to the chamber for the next ~24 hours. At the end random speckles for DICM were applied using matte spray paints (red and black) on full face (xy-plane as shown in Fig. 2) of each specimen by adopting procedure explained in one of the studies in our laboratory [6].

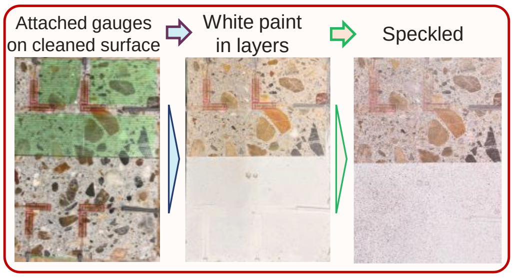

Fig. 2 Specimen preparation for DICM

2.3 Test Methods

(1) Water Absorption Test

The previous studies like [7] evaluate the water absorption (i.e. sorption) in cement-based materials and follow procedures in ASTM C1585 [2], which adopt the one-dimensional water absorption test configuration considering capillary rise case (in which absorption is opposite to gravitational effects Hall C. [8]). However, in this study the authors also performed one dimensional water absorption test on concrete thin slice specimens but adopted another configuration reviewed by Hall C. [8] which allowed horizontal water penetration into

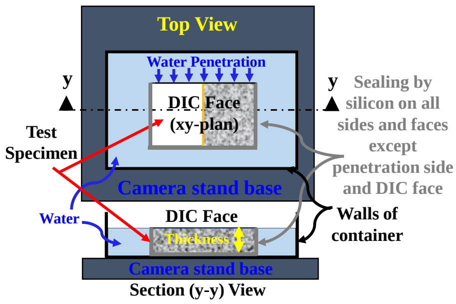

Fig. 3 Placement of specimen in water container placed over rigid/stable base of camera stand for DICM

concrete materials, where the absorption rate is independent of gravitational effects, rather it is governed by hydrostatic forces and that the unsaturated capillary flow in porous media of concretes. Of course, a constant water depth was always maintained with specimen thickness throughout the test (as indicated in side view of Fig. 3). Two types of data were collected during the water absorption process, which lasted 2,700 minutes: (i) recordings of surface strains and (ii) images captured from the top face of the specimen at one-minute intervals.

(2) Digital Image Correlation Method (DICM)

In this study 2D-DIC analysis was performed by involving one high grade charged couple digital camera with maximum resolution of 6000 x 4000 pixels, and one pair of LED lights. As shown in Fig. 4 the camera was mounted perpendicularly at ~380 mm focusing on top of the flat surface of the specimen (i.e. xy-plane). GOM Correlate 2019 software package was used as correlation tool.

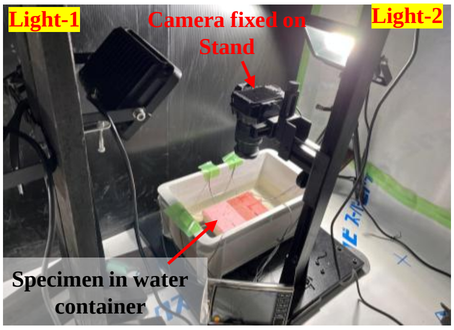

Fig. 4 Set up for 2D-DICM with Water Absorption Test

3. APPLICATION OF DICM TO EVALUATE CONCRETE VOLUME CHANGE DURING WATER PENETRATION

Fig. 5 shows the in-plane strains developments measured in terms of maximum principal strain on both the halves (i.e., P and NP) at different times with respect to time of initial contact with water (i.e. 0 minute) in low strength concrete with W/C=0.65. It is observed that strain gradually increases depending on saturation. However, the strain values on P and NP sides are quite different i.e. NP surface shows high strain intensity in

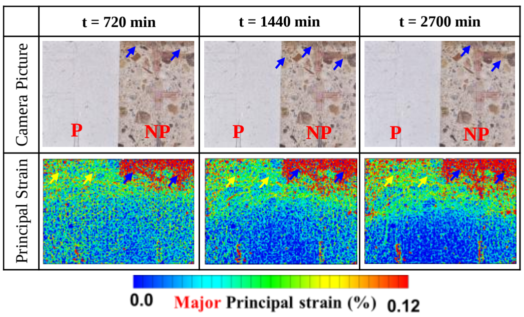

Fig. 5 Influence of water penetration on measurements in DICM considering P and NP surfaces of low strength concrete

saturated areas compared to that on P side surface as pointed by arrows. It was because the surface contrast on NP side changed due to saturation which could mislead algorithm used in DIC software for correlations and thus strains on NP side can be regarded as unnatural, and unreliable. Therefore, herein after only P side results are presented in this study.

3.1 Strain recorded by Surface Strain Gauges Vs Strains by DICM on P Side ($P\varepsilon_{DICM}$ Vs $P\varepsilon_{Gauges}$)

Fig. 6 shows the measurements of strains on the surface of the specimens (in the xy-plane) recorded by surface strain gauges (solid line) and calculated in DIC (dashed lines) during water absorption in relation to the wetting duration (t in minutes) for three strength cases. In these figures, the blue and red lines show the strains recorded at gauge position-1 (near the surface in contact with water, ref. Fig. 1) in x-axis and y-axis directions, respectively. Similarly, the green and grey lines show the strains recorded at gauge position-2 (at the middle of the width of the specimen, ref. Fig. 1) in x-axis and y-axis directions, respectively. Note that the strains in the x and y directions indicate deformation caused by water absorption in the direction perpendicular and parallel to the water penetration direction, respectively. Moreover, the strains in DICM software were calculated as mean strain averaged within the length equal to that of the gauge (i.e., 10 mm). It can be seen, strains calculated in DICM are in very good agreement with those measured by surface strain gauges, confirming the validity of the application of DICM during water absorption.

Surface strain gauges at position-1 started indicating deformations in specimens immediately after contact with water, but those at position-2 delayed in all strength cases. This phenomenon corresponds to the fact water ingress has an instant effect on the volume changes in concrete materials owing to the hygroscopic nature of the cement hydrates (i.e. the C-S-H gel), which results in expansion as illustrated in a study by Igarashi et al. [4]. Also, the volume changes observed in this study are consistent with the observations in a study by [9].

It is observed that x-axis direction strain in all cases has a gradual rise with the wetting duration, which corresponds to the continuous and uniform increase in the level of saturation (i.e., expansion) within the concrete materials. However, the same specimen in its y-axis (at position-1) initially experienced compressive strains reaching a maximum value of -0.0027%, -0.0057%, and -0.0092% after t = 51, 109 and 397 minutes in low, medium, and high-strength concretes, respectively. Similarly, at position-2, maximum compressive strains of -0.0046%, -0.0053%, and -0.0028% were attained in the y-axis direction after 925, 2312, and 2700 minutes in low, medium, and high-strength concretes, respectively. The occurrence of compressive strains along y-axis in all strength cases can be attributed to the bending deformation in third axis (i.e. vertical) direction caused as part of isotropic three-dimensional volumetric expansion resulted from of the internal swelling reaction of cement hydrates [3], [9].

Moreover, compressive strains occur at the waterfront and later part as clearly observed in strain distribution in DICM and is also confirmed from strains by y-axis gauge. E.g., the gauge strains remain

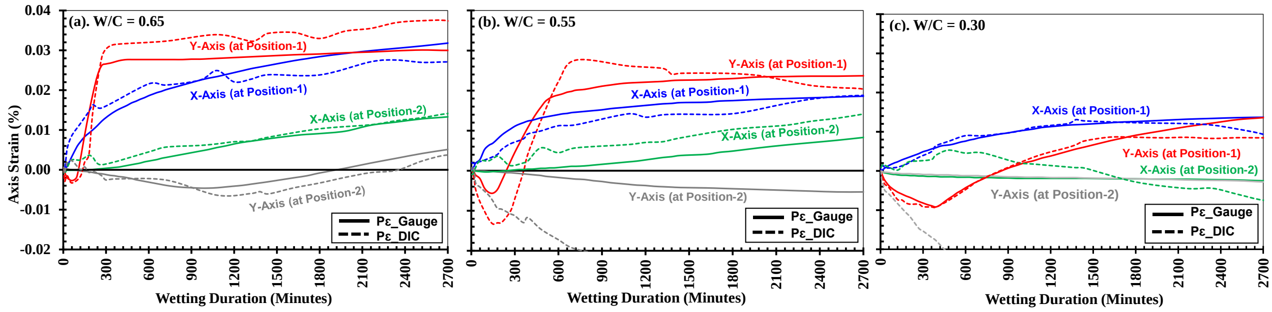

Fig. 6 Comparison of strains recorded by surface strain gauges with those measured by DICM on P side half of face for DICM in concretes with different strengths (i.e. (a) low, W/C = 0.65, (b). Medium, W/C = 0.55 and (c). High, W/C = 0.30) with increasing wetting

compressive when underneath part of the gauge is partially saturated, but it changes to tensile strain after its underneath part becomes completely wet (i.e. where expansion starts), as illustrated in Fig. 7 in which grey lines indicate possibilities of strains developed in each direction at the shown level of saturation. It is noted that the strains calculated in DICM include not only the effect of volumetric expansion in concrete materials but also an effect of bending deformations which depend on the specimen stiffness.

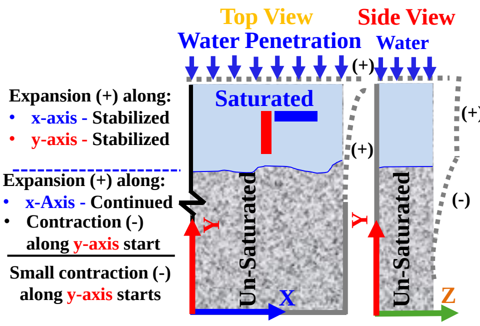

Fig. 7 Mechanism of deformations caused by swelling of cement hydrates in concrete materials

In overall, after 2700 minutes of water absorption, the low-strength concretes experienced 0.03%, medium-strength 0.0237%, and high-strength 0.0136% strains along the x-axis at position-1. The differences in the strain development correspond to the presence of pore fractions causing variations in the rates of water absorption penetrating through porous media of concrete materials. Since these strain measurements are at specific points, utilizing DICM allows the evaluation of overall water absorption characteristics by observing full-field strains in the saturated part more accurately and efficiently.

3.2 Evaluating Water Absorption Characteristics in Concrete Samples

From strain distributions along x- and y-axis recorded by gauges it was observed that the progression of the y-axis strain is prominent during one dimensional water absorption because water movement is also predominantly along the y-axis. That is strain distribution along y-axis especially in DICM clearly defines the boundary by indicating positive strain (due to expansion) and negative strain (due to contraction) in saturated and unsaturated regions, respectively (as can be seen in strain maps by DICM in section 3.3). So in this study, water absorption depth is determined by considering strains plots along y-axis.

Fig. 8 illustrates the procedure to determine the water absorption depth (d) in low strength concrete specimen at t = 120 minutes. A moving average of the strain was calculated along equally spaced six lines for data points within a three mm range on each line drawn along the width (W, y-axis) on P side starting at 0 mm (near the water), as shown in section 3.3 (Fig. 10 original pictures). Finally, the average (mean) of these six lines was calculated, and a single (red) line was plotted along width, which was used to estimate the water depth(d). As discussed in section 3.1 that the strain value suddenly changes, at the water front, from tension to small compression value. The water penetration depth is defined by this change point (as shown in Fig. 8).

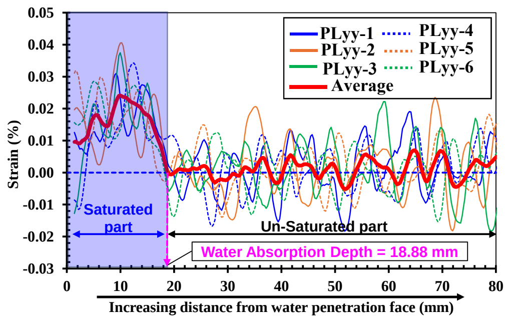

Fig. 8 Definition of calculating depth of water penetration with respect to penetration face by using strain distribution along y-axis using DICM

Fig. 9 shows the strain variations along y-axis at different times (t). The absorption depth (water front) is determined at the respective time considering the threshold strain (i.e. 0 % as marked in Fig. 8). It shall be noted that same procedure was adopted to determine water absorption depths in all cases considered in this study.

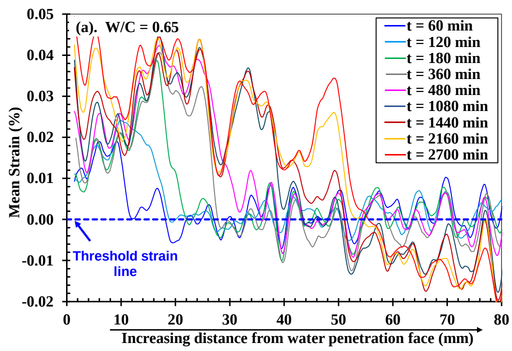

Fig. 9 Variation in mean strain distribution along y-axis obtained in DICM (as shown in Fig.8) at different wetting durations

3.3 Full-Field Deformations with increasing Saturation in Concretes of Different Strengths

Fig. 10 shows the full field strain measurements in y-axis direction on paint side surface of specimens of three concrete strengths. The strain progression with the increasing saturation level is presented at different time intervals. It is very clear that strain development at the points closer to the water is higher which indicates the higher degree of saturation in mortar part of the concretes. The marked vertical lines in original pictures and the horizontal yellow (dashed) line represent the lines for strains along y-axis and the waterfront determined by strain distribution plots (as explained in Fig. 9), respectively. It can be clearly observed, at each time interval low strength concrete has more areas covered by positive strains indicating more water absorption (thus more expansion) than medium strength, whereas the high strength concrete has the least areas showing positive strains owing to the least porosity and hence very low rate of water absorption.

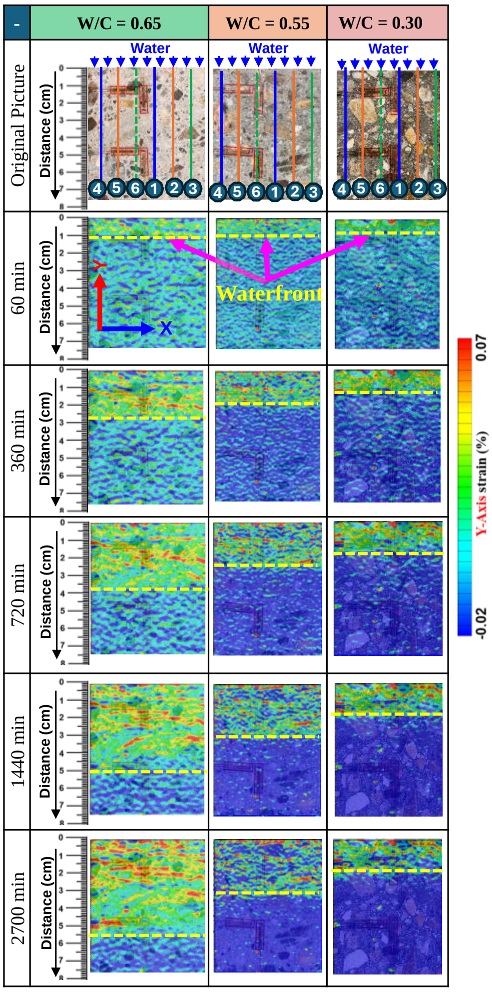

Fig. 10 Comparison of full field strain variations along Y-Axis with increasing wetting durations in (a). low, W/C = 0.65; (b). medium, W/C = 0.55 and (c). high, W/C = 0.30 strength concretes

After determination of water absorption depths by strain distributions by DICM, the depth (d) versus square root of time ($t^{0.5}$) plot was obtained for all strengths (Fig. 11). So utilizing these plots, the rate of water absorption was determined as slope of best fit line in initial part of the curves in all strength cases. Studies related to absorption test e.g. [7], [9] considered slope of a line drawn in d vs $t^{0.5}$ plots within initial six hours as initial rate of absorption based on [2] but in current study the movement of water absorption front continue to increase after six hours depending on each strength case as can be seen in Fig. 11. Therefore, authors considered the slope of best fit line (to the clear deviation point i.e., up to 1320 minutes in low strength and 720 minutes in medium and high strength concretes) as the initial rate of absorption I_1 (see the dashed red lines in Fig.11). This deviation, however, follow similar trends as in previous studies by authors [4]. Moreover, these observations in DICM have also been complemented in a numerical study conducted by Srimook et al. [10]. It is observed that lower the strength (i.e. W/C = 0.65), the higher will be the initial rate of absorption and vice versa. Moreover, these results are consistant with those obtained in studies e.g., [7], which perform gravimetric measurements.

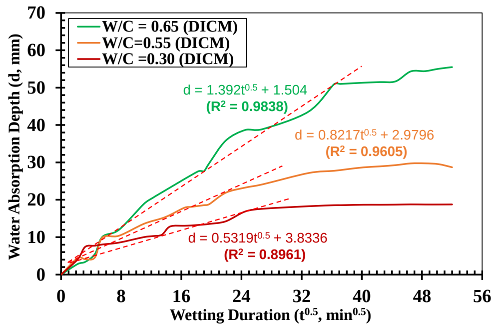

Fig. 11 Increasing water absorption depth (determined by DICM in low, medium and high strength concretes) versus ($t^{0.5}$)

4. RELATIONSHIP BETWEEN WATER ABSORPTION CHARACTERISTICS AND THE COMPRESSIVE PROPERTIES OF CONCRETES OF DIFFERENT STRENGTHS

The above determined rate of absorption is plotted against the compressive properties i.e. f_c' and E of concretes specimens of different strengths determined from compression test after completing water absorption test. It is observed that the rate of absorption decreases with the increase in both the f_c' and E as shown in Fig.12.

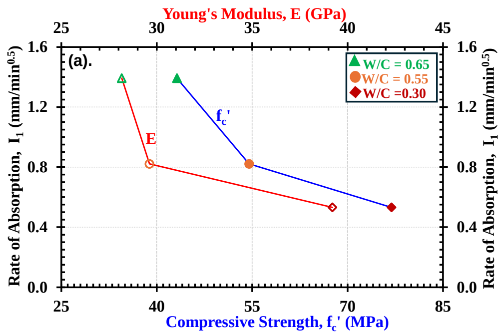

Fig. 12 Relationship between Compressive properties (f_c' and E) of different strength concretes with the rate of absorption determined by DICM

In Fig.13 the relationship between the compressive properties and maximum expansive strains in y-axis at position-1 (achieved after wetting duration of 2700 minutes) is given. The deformability due to saturation also relates to the compressive properties of the concretes in similar manners as the rate of absorption did. Thus, it can be expected that when strength is lower, the possibility to experience deformations (especially during water absorption due to less resistance offered by material against water penetration) will be higher and hence higher will be the chances for durability deteriorations.

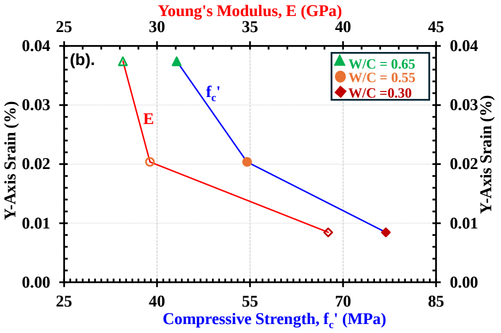

Fig. 13 Relationship between f_c' and E of different strength concretes with the maximum expansive strains along Y-Axis at t = 2700 min determined by DICM

Since all the test specimens in this study were prepared/conditioned in same way, equally cured and tested at same ages, thus it can be stated that all the concretes were equally hardened depending on their mix design parameters. Also, irrespective of traditional approaches real time monitored data by using DICM is used to determine absorption depth/rate. So, the relationships shown in Figs. 12 and 13 can be considered more realistic and a good indicator of the differences in the microstructures of concrete materials and mix design parameters. Thus, more accurate durability performance of concrete materials can be estimated i.e. concrete with lower strength allows more rapid water penetration and other liquids or ions owing to more pore fractions.

5. CONCLUSIONS

In this study, water absorption characteristics (depth, rate and strain generation) during one dimensional water absorption test were evaluated by utilizing DICM for oven dried thin slice specimens of concrete with three different strengths based on different W/C ratios. The following conclusions can be drawn from observations in this study;

(1) Water ingress has an instant effect on the volume changes in concrete materials owing to the hygroscopic nature of the cement hydrates (i.e. the C-S-H gel). So, deformability, absorption depth and the absorption rate are strongly influenced by the composition and DICM can provide more reliable evaluations in this course to define durability.

(2) DICM provided real time monitored information on water absorption and progression in resulting deformations (strains) during one dimensional water absorption, which could efficiently differentiate between concrete materials of different mix compositions.

(3) Concrete materials with lower W/C ratios (high strength) experience lower strain rate, lower deformability compared to others with higher W/C ratios. A good relationship was detected in this study from single specimen in each case, however further detailed evaluations can be executed by adopting this framework.

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