Modal Parameters of Concrete Beam under Varying Moist Curing Conditions

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Abstract. Natural frequency, damping, and mode shape are the modal parameters of a system which can be used to assess dynamic performance of the system. These parameters however would vary if the system happens to experience changes physically or chemically, say exposure to different environmental condition. Over the years, researchers over the world have put considerable efforts in investigating different factors which potentially causing changes in modal parameters in concrete as a part of developing Structural Health Monitoring (SHM) system. In this paper, the effects of varying moist curing condition on modal properties of concrete beam specimens were investigated and presented. In order to manipulate the moist curing condition, two concrete beams were prepared and cured for different period of time, i.e. standard 28 days and up to 58 days respectively. Modal tests were conducted once every two days starting from the twenty-eighth (28th) day for 15 times using triggered hammer method. Dynamic responses and Modal Assurance Criterion (MAC) values of both specimens were calculated to identify the correlation between mode shapes under different curing condition. This study found that the change in frequencies for specimen with prolonged curing shows smaller and more consistent decrement as concrete ages, while the MAC values are also higher and less fluctuated in general than that of specimen which only undergone standard curing. Based on these findings, it is noticeable that extendedly moist curing improved the performance of modal properties in young concrete besides mechanical properties.

Introduction

While underperformance of concrete with unsatisfactory moisture content due to improper curing is one of the growing concerns among engineering communities, numerous studies were conducted to investigate the moisture in concrete subjected to different curing [1]. Curing of concrete may help in retaining adequate amount of free water in cement paste for cement hydration to produce bonding effect and transpire the durability and strength to concrete. In fact, more other concrete properties moisture distribution, shrinkage and cracking are also significantly affected by curing as discussed by [2] in their writing.

Concrete may loses many of its quality if it is not properly cured, agreed [3], as the author observed that concrete is usually mishandled at construction sites. As hydration of cement only take place in water filled capillaries, curing of concrete is highly recommended and on the other hand to prevent loss of water from concrete via evaporation from the capillaries. Uncured concrete specimen exposed to dry air would only develop 50 % of strength at 6 months as compared to that of concrete cured 14 days before being exposed to dry air.

There are indeed many ways to evaluate the performance of concretes under various moisture content depending on the parameters desired, including compression test, split tensile test, and modulus of elasticity test [5]. Ideally, demolishment of old structures and replace them with new buildings would be more cost effectiveness than repairing and preserving the old structures, but in many cases damaged civil structures especially those with social importance and historical values cannot be economically replaced by any mean. It is therefore important to monitor the structural health by Non-Destructive Examination (NDE) method and to fix the damages detected to prevent further deterioration or any undesired failure in performance and appearance of the structure. Many efforts have been carried out to verifying Vibration-based Damage Detection (VBDD) testing as one of the most effective NDE techniques, and has been vastly adapted [6], albeit it is not common in Malaysia yet, to examine changes in modal parameters such as mode shapes and natural frequencies by measuring the vibration response as functions of the physical properties of the system in region of damage.

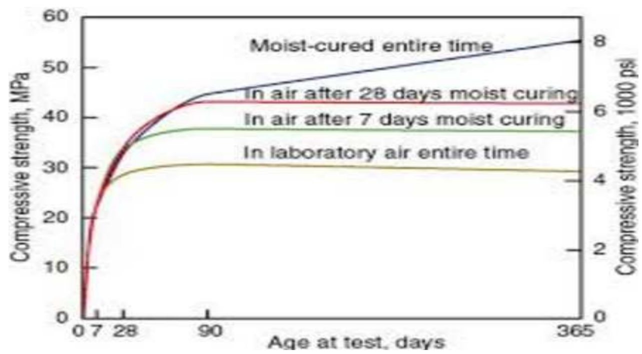

Figure 1: The Influence of Moist Curing on the Strength of Concrete [4]

Modal test is a subset of SHM, and is among the growing techniques vastly used in damage detection by observing the change in dynamic parameters of the instrumented structure. Modal test can be further broken down into several methods including the well-known VBDD method, which were first invested by oil and gas industry in 1970s to examine modal performance their offshore structures, according to [7], until experts in aerospace picked up the topic later in that decade.

Civil engineers began their journey in exploring VBDD assessment by applying it to bridge structures since early 1980s, starting with basic modal parameters (mode shapes, natural frequencies, and damping ratios) and their derivatives (mode shape curvature, and etc.). Since then, more and more advanced techniques that involve complex methods such as hybrid matrix and eigen-structure assessments have emerged among civil engineering community for damage detection in complicated structures. However, all of these methods were generally derived from elementary equations of motion for the physical properties of the materials. Any change in physical properties / damage occurred may affect the modal properties [8], thus detection of damage location and its severity is made possible.

Most of these research works are solely numerical examples, while those data obtained by utilizing experimental modal testing methods are limited. This study intended to determine the modal parameters of concrete under different moist curing conditions by using the experimental modal testing methods with the aid of several software in data acquisition and analysis.

Objectives

The study is conducted using the experimental triggered hammer method with the aid of several software in data acquisition and analysis to determine the modal parameters of concrete under different moist curing conditions. The principal objectives are reckoned as below:

1. To investigate the change in frequencies of concrete beam at different curing phases;
2. To identify the change in mode shapes of concrete beam at different curing phases, and;
3. To observe the effect of moist curing to dynamic properties of concrete beams.

Methodology

Two concrete beams specimens of size 100x100x500 mm were prepared and cured for 28 days. One of the specimens were then extendedly cured throughout the modal test (28 more days in addition to original 28 days) is referred to as Specimen C01, while the other one (Specimen C02) was removed from water tank and left in air as the modal test began.

Table 1: Curing Conditions

Concrete Codes	Days in Mould	Days in Water	Days in Air
C01	1	28+28	0
C02	1	28	28

Modal tests using triggered hammer method (1 Excitation, 1 Response) were then conducted to collect the responses once every two days for fifteen (15) times at nodes of the tested specimens. Prior to the first modal test, both specimens were divided into 6 segments and were marked with marker pen to resemble their 7 nodes spanning along the beams as shown in Figure 2 below. Pinned supports were placed underneath both ends (10 mm from both edges were spared as redundants) to elevate the specimens so that the specimens can vibrate freely at most points during triggered hammer data acquisition tests.

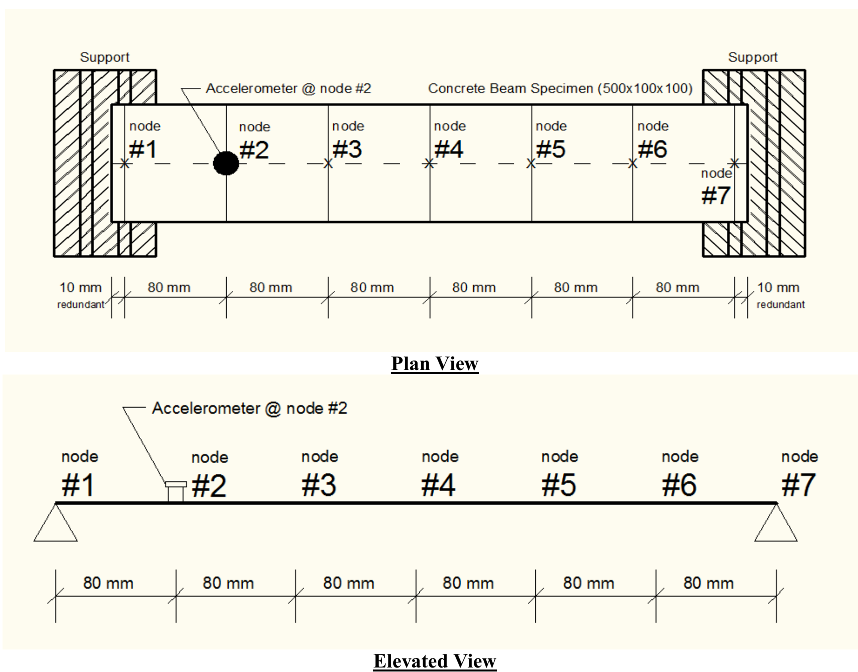

Figure 2: Depiction of Concrete-beam Specimens Setup with Labels during Modal Tests (Not to Scale)

During the modal test, dissatisfactory hits can be rejected (See Figure 3 for the procedure), otherwise proceed to the next point after 3 hits. The Fast Fourier Transform (FFT) graphs will update after every hit with a new averaged graph, where DEWESoftX converts an input signal applied to system to a measured output Transfer Function. Frequency range of high stress and dangerous resonance can be determined by specifying a limited operating range when the transfer characteristic of a structure is known.

Modal paramters namely natural frequency and mode shape were then extracted from the responses with the aid of DEWESoftX and ME'scopeVES. Curve-fitting was conducted by matching empirical data to mathematical expression or analytical function, usually done by minimizing the squared difference between the data obtained and the function values. Each resonance frequency peaks in the Frequency Response Function (FRF) plots gives a set of mode shapes as a result of post-processing analysis.

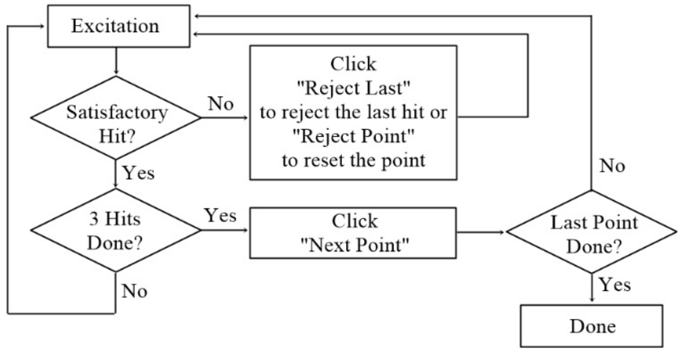

Figure 3: Flowchart showing the Procedure to Roving Hammer Method Modal Test

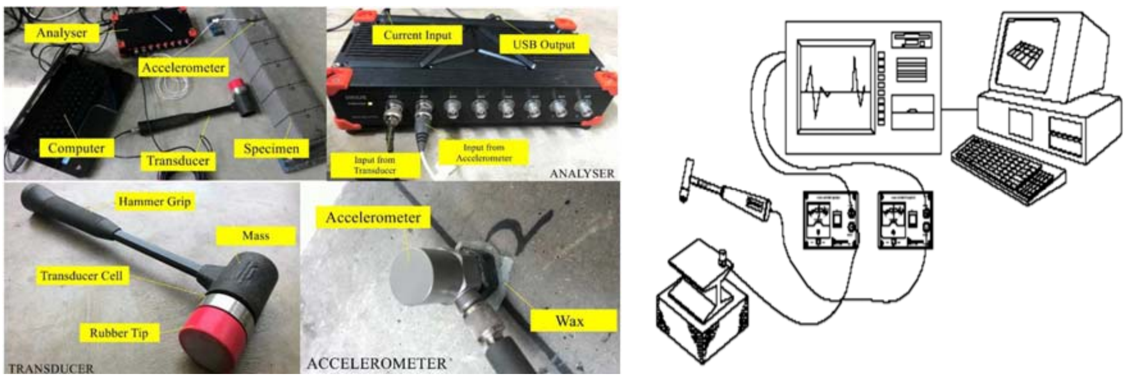

Figure 4: Setup of Modal Hammer Testing

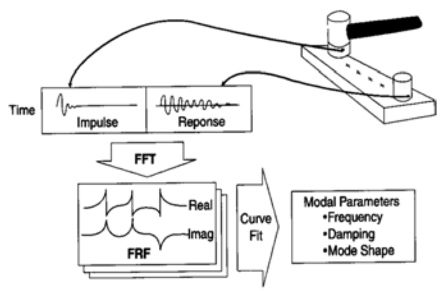

Figure 5: Signal Post-Processing Steps

Mode shapes of the specimens were compared to the mode shape matrix for initial state at each modes based on Modal Assurance Criterion (MAC) values. The function of MAC may provide researchers with a measure of consistency or degree of linearity between estimates of modal vector, which gives an additional confidence factor when evaluating modal vector from different modal parameters or locations of excitation. In order to ease the comparing collected of modal vectors, [9] suggested that a correction approach can be done before calculating the MAC by “correcting” or “completing” the experimental modal vectors if some Degree of Freedoms (DOF) could not be measured, by multiplying the modal vectors with the Modal Scale Factor (MSF).

$$\text{MSF} = \frac{[A]^T[\text{B}]}{[B]^T[\text{B}]}$$

where, MSF = Modal Scale Factor; A = Mode Shape Matrix for Other Cases; B = Mode Shape Matrix for Initial State (TEST 01)

$$\mathrm{MAC}_{A,B} = \frac{|\sum_{i=1}^{n} \varphi_i^A \varphi_i^B|^2}{\sum_{i=1}^{n} (\varphi_i^A)^2 \sum_{i=1}^{n} (\varphi_i^B)^2}$$

where, φ^A = Modified Mode Shape Matrix (Other Cases); and φ^B = Modified Mode Shape Matrix (Initial State)

Results and Discussion

Modal parameters are extracted from FRF signal time response of a structure. In most cases, natural frequencies obtained are more accurate than mode shapes as the frequencies are related to time response of the testing structure. [10] suggestion on high level of significance in the relationship between moist curing and frequency coincides with the results of this study where the extendedly cured specimens give generally more consistent and smaller range of frequency changes that of specimen which was only cured for standard 28-days.

In practice, natural frequency of a structure decreases when concrete ages. The significant interaction between concrete age and frequency was suggested by [10]. Fluctuated patterns can be observed in the frequencies of both specimens. However, it is also perceivable by looking at the whole of Table 2 that the latter tests produced smaller natural frequencies of all modes than that of the earlier tests.

Table 2: Summary of Natural Frequencies (Hz) of Specimens C01 and C02

TEST	**Concrete Age (days)**	**Natural Frequencies (Hz)** Specimen C01 (28d+28d Extended Curing)			Specimen C02 (28d Standard Curing)		
		Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
TEST 01	28	131.0	323.0	683.0	89.2	380.0	726.0
TEST 02	30	124.0	397.0	677.0	162.0	368.0	692.0
TEST 03	32	111.0	360.0	616.0	82.1	311.0	635.0
TEST 04	34	138.0	318.0	648.0	115.0	371.0	660.0
TEST 05	36	134.0	333.0	805.0	184.0	317.0	713.0
TEST 06	38	159.0	314.0	617.0	120.0	306.0	634.0
TEST 07	40	162.0	283.0	687.0	104.0	374.0	637.0
TEST 08	42	134.0	381.0	757.0	107.0	306.0	685.0
TEST 09	44	179.0	337.0	651.0	186.0	353.0	614.0
TEST 10	46	100.0	298.0	622.0	109.0	346.0	701.0
TEST 11	48	161.0	322.0	592.0	129.0	373.0	606.0
TEST 12	50	120.0	369.0	684.0	150.0	319.0	713.0
TEST 13	52	114.0	331.0	638.0	179.0	370.0	661.0
TEST 14	54	122.0	290.0	664.0	102.0	383.0	663.0
TEST 15	56	111.0	373.0	609.0	127.0	329.0	667.0

Generally, the differences between initial frequencies (TEST 01) and final frequencies (TEST 15) were around 10 % to 15 % for all modes of Specimen C01, while changes in frequencies for Specimen C02 give a wider range of 8 % to 42 %. These changes are prompting that the changes in natural frequency are notable as they have exceed about 5 % according to [11], thus this shows that there are effect of moist curing on modal frequencies. The smaller range of changes also shows that the change of frequencies in Specimen C01 is more consistent than that of Specimen C02.

The ranges of change by comparing the initial frequency (TEST 01) and final frequency (TEST 15) are more consistent in Specimen C01 (ranging from 10.83 % to 15.48 %) than that of Specimen C02 (ranging from 8.13 % to 42.38 %). Such consistency in frequency shift may be contributed by extended curing undergone by Specimen C01. This improvement of frequencies is due to extended moist curing coincides with the findings of [3], who argued that concrete may loses many of its quality if it is not properly cured. Adequate curing is highly recommended as hydration of cement only take place when concrete is exposed to water which helps in improvement of concrete properties.

Natural frequencies, according to [12], varies rapidly during excitations and might not always trackable. In other word, dynamic responses of damaged structure are non-linear and the change in stiffness may be wildly complicated and hysteric in most cases.

The statement is unable to completely explain the fluctuated patterns throughout the experiments, and some unexpected increment of natural frequencies. However, the more consistent variation of frequencies for Specimen C01 can be attributed to prolonged moist curing, as supported by [10], who suggested that there is a ninety-percent level of significance in the relationship between moist curing and frequency.

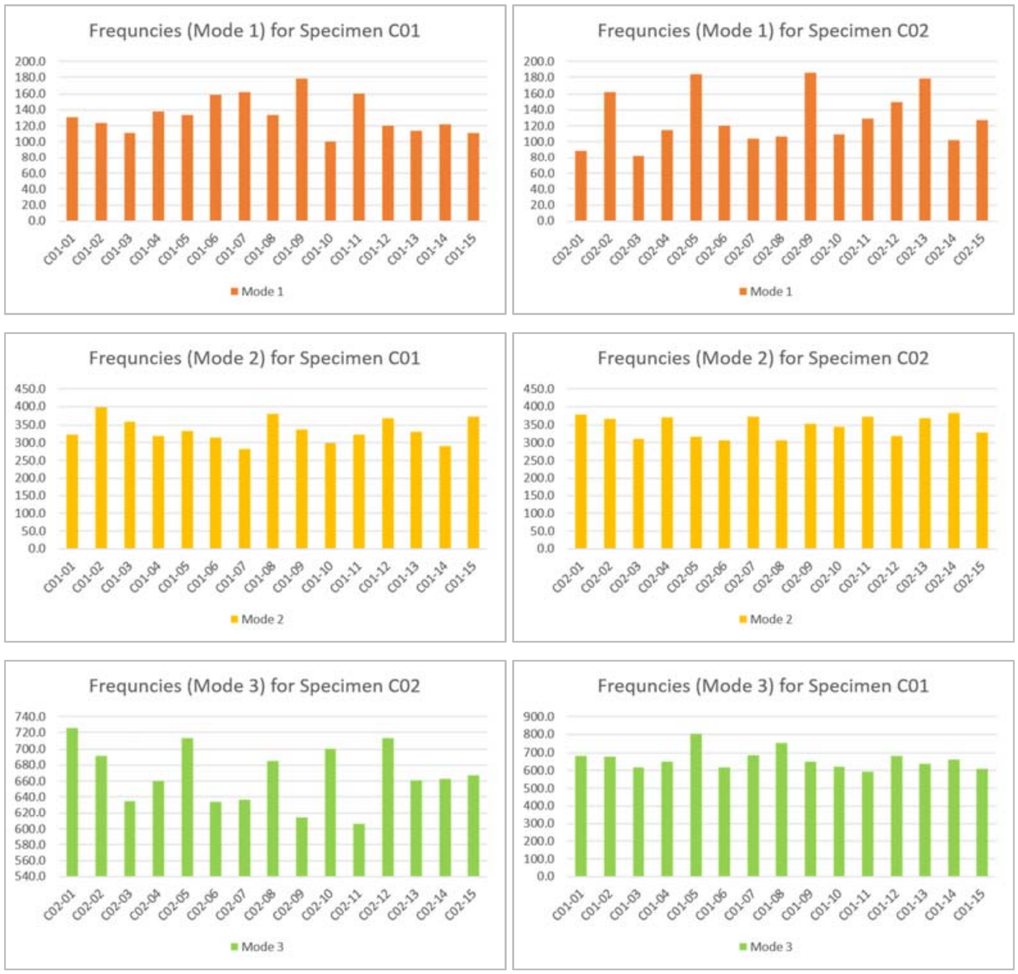

Figure 6: Changes in Frequencies for C01 (Left) and C02 (Right) of the First Three Modes

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Table 3: Summary of Experimental Damping (%) of Specimens C01 and C02

TEST	Damping (%)					
	Specimen C01			Specimen C02		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
TEST 01	1.99000	0.08600	0.01390	2.46000	0.03000	0.00186
TEST 02	2.43000	0.01840	0.00160	0.34100	0.00497	0.03560
TEST 03	0.43500	0.12700	0.05550	1.20000	0.11300	0.03040
TEST 04	0.51600	0.03580	0.00427	1.41000	0.04160	0.00334
TEST 05	0.54700	0.09540	0.03250	0.00700	0.16000	0.01670
TEST 06	2.34000	0.12500	0.01320	1.22000	0.02510	0.01820
TEST 07	0.02350	0.01640	0.03460	0.05560	0.00436	0.02410
TEST 08	0.69300	0.01780	0.00101	0.43000	0.01290	0.00127
TEST 09	0.08400	0.00005	0.03300	0.03690	0.02800	0.00149
TEST 10	0.26200	0.02290	0.02570	0.10400	0.04570	0.08320
TEST 11	0.44500	0.00911	0.01990	0.01800	0.06790	0.00842
TEST 12	0.21500	0.01010	0.00307	0.00608	0.01640	0.02350
TEST 13	0.02560	0.27300	0.02760	0.73600	0.12600	0.00408
TEST 14	2.65000	0.41800	0.02900	0.15000	0.05350	0.00111
TEST 15	0.20600	0.02240	0.01310	0.04720	0.01030	0.00518

On the other hand, damping ratio of Specimen C01 ranges widely from 0.00005 % to 2.65000 %, while Specimen C02 has damping ratio between 0.00111 % and 2.46000 %. The change of damping ratio for both specimens throughout the experiment shows wildly fluctuated patterns. Such inconsistency aligns with findings in tests conducted [13] as well as [14], which gave inconsistent change with undetectable patterns in damping ratio in their RC bridge and steel plate Girder Bridge assessments, thus proving that damping is not suitable to detect modal changes in concrete specimens.

Mode shapes, however, require spatial distribution of responses under precisely controlled experiment in order to obtain accurate mode shapes using force appropriation method. While in many curve-fitting software visualize shape magnitudes as animated mechanism, it only helps users to understand the potential deformation if that mode of the structure is excited by the force function. Therefore, measurement of accurate mode shapes may be very complicated without defining an excitation force. For this experiment, only the first 3 modes of specimens lying within frequency range of 0 to 1000 Hz were identified via curve-fitting process with the aid of ME'ScopeVES using Ortho Polynomial Method to identify modal parameters including mode shapes and shape magnitudes.

In order to make comparison between mode shapes, [15] and [9] have proposed the MAC approach to check the correlation and overall differences between two sets of mode shapes. By referring to their suggestion, MAC for 3 modes of 2 specimens were calculated using the respective mode shape at TEST 01 (Initial State) as reference matrices to compare with subsequent mode shape matrices in this experiment. MSF were also calculated beforehand to modify those mode shape matrices.

It is noticeable that overall tests of Specimen C01 give higher MAC values (much closer to 1.0000) than that of Specimen C02. The range of MAC values is also smaller for Specimen C01 in general excluding some exceptionally lower values, comparing to that of Specimen C02 which give a wider range. This shows that Specimen C01 has properly developed modal properties as a result of extended moist curing. This coincides with the findings of [16], who suggested concrete properties such as strength and durability may not fully developed without adequate curing period. Researchers, [17] also agrees that concrete curing should be done appropriately during the early stage of hardening in order to produce a good concrete with developed durability, strength, and other mechanical properties.

Table 4: MSF and MAC for both Specimen C01 and C02 at the First Three Modes

Mode	**Test**	**Extended Curing Case (Specimen C01)**			**Standard Curing Case (Specimen C02)**		
		Frequency (Hz)	MSF	MAC	Frequency (Hz)	MSF	MAC
1	01	131.0	1.0000	1.0000	89.2	1.0000	1.0000
	02	124.0	1.2713	0.9372	162.0	0.3237	0.6811
	03	111.0	0.2573	0.9623	82.1	1.0077	0.9639
	04	138.0	0.0581	0.8031	115.0	0.4817	0.9293
	05	134.0	0.1397	0.9703	184.0	0.0372	0.8298
	06	159.0	0.4119	0.9540	120.0	0.7283	0.9181
	07	162.0	0.2235	0.8837	104.0	0.0532	0.9346
	08	134.0	0.0477	0.1249	107.0	0.0936	0.8756
	09	179.0	0.0085	0.0142	186.0	0.0044	0.0150
	10	100.0	0.0198	0.9447	109.0	0.3403	0.8510
	11	161.0	0.2264	0.4532	129.0	0.0253	0.8904
	12	120.0	0.1531	0.9569	150.0	0.0227	0.7033
	13	114.0	0.0046	0.9882	179.0	0.0957	0.7512
	14	122.0	1.3420	0.9869	102.0	0.0381	0.9239
	15	111.0	0.1272	0.9610	127.0	0.0867	0.8272
2	01	323.0	1.0000	1.0000	380.0	1.0000	1.0000
	02	397.0	-0.0829	0.0438	368.0	-0.4119	0.1574
	03	360.0	0.2127	0.0228	311.0	0.1593	0.2459
	04	318.0	-0.3637	0.7252	371.0	0.3042	0.3838
	05	333.0	0.2997	0.7336	317.0	0.7761	0.2190
	06	314.0	0.2995	0.1414	306.0	0.1728	0.3331
	07	283.0	0.3815	0.2824	374.0	0.5280	0.1261
	08	381.0	-0.1621	0.5793	306.0	0.4364	0.0971
	09	337.0	-0.0105	0.0048	353.0	0.1234	0.0114
	10	298.0	0.0100	0.0003	346.0	0.4937	0.6732
	11	322.0	-0.0199	0.0101	373.0	0.2418	0.3826
	12	369.0	-0.0223	0.0100	319.0	0.0804	0.1563
	13	331.0	1.2614	0.6765	370.0	0.5510	0.5838
	14	290.0	0.2953	0.2091	383.0	0.3650	0.2562
	15	373.0	0.4366	0.9458	329.0	0.0535	0.0761
3	01	683.0	1.0000	1.0000	726.0	1.0000	1.0000
	02	677.0	1.5536	0.0748	692.0	4.6214	0.3717
	03	616.0	2.1028	0.7090	635.0	-0.2834	0.0090
	04	648.0	0.7399	0.1761	660.0	-0.5764	0.1117
	05	805.0	0.0468	0.0004	713.0	-0.1023	0.0009
	06	617.0	0.4628	0.3674	634.0	-1.4098	0.1613
	07	687.0	3.9544	0.3096	637.0	0.2750	0.0560
	08	757.0	1.4473	0.0943	685.0	-0.0422	0.0003
	09	651.0	3.7275	0.5109	614.0	0.0761	0.0006
	10	622.0	1.5915	0.6335	701.0	2.9769	0.3613
	11	592.0	-0.0230	0.0001	606.0	0.6437	0.0721
	12	684.0	0.1821	0.0049	713.0	1.2138	0.0315
	13	638.0	-1.6064	0.1148	661.0	-1.3356	0.2068
	14	664.0	-1.2019	0.0247	663.0	-0.5154	0.0363
	15	609.0	-0.1109	0.0965	667.0	-0.0667	0.0013

It is noticeable that there are some fluctuation in MAC values in both specimens for all the modes. The inconsistency in MAC values may due to noise mode, which according to [18], sometimes the mode obtained may be deviated from the theoretical mode shapes which are based on modal analysis of numerical model of a structure, whereby those are not basis modes. Mode screening may be performed with the knowledge on theoretical mode shapes of the structure, but it is beyond the scope of this study.

While MAC values show level of correlation and overall differences between two sets of mode shape, the reduction in MAC values prompted a numerical basis for detecting changes in modal parameters. Generally, the overall tests of Specimen C01 give higher MAC values (much closer to 1.0000) than that of Specimen C02. As for Mode 1, Specimen C01 also exhibit a closer ranged changes throughout the tests, thus having a better hydrated concrete properties comparing to that of

Specimen C02. While Specimen C02 was only cured 28 days (without extended curing like Specimen C01), concrete may still not fully develop their strength, durability and other concrete properties without adequate curing period for cement hydration, as suggested by [16] and [17]. Concrete curing should be conducted appropriately during the early stage of hardening in order to produce a good concrete.

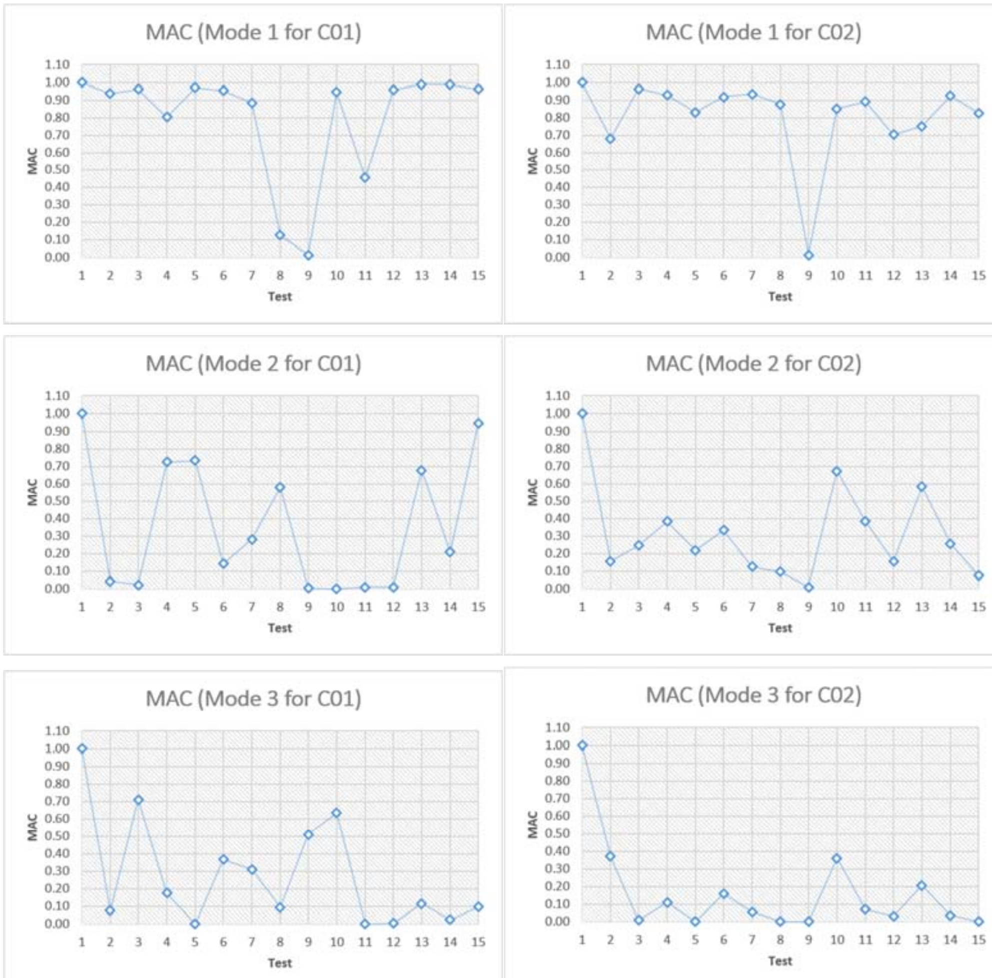

Figure 7: Graphical Presentation of Changes in MAC Values at the First Three Modes

The summary of findings for this study on effect of varying moist curing condition on modal parameters of concrete specimens are as below:

1. Damping is not suitable to detect modal changes in concrete specimens as the values fluctuate wildly without a consistent pattern;
2. Changes in frequencies (comparing initial and final) for Specimen C01 are more consistent than that in all 3 modes compared to that of Specimen C02, as extended curing enhance further cement hydration and development of modal properties in young concrete, and;
3. Specimen C01 give higher MAC values (much closer to 1.0000) than that of Specimen C02 in general, showing that specimen which is cured for a longer period gives a more consistent modal properties and higher correlation between initial and final mode shapes.

Conclusion

The changes in frequencies and mode shapes under varying moist curing condition has been justified. Demonstration of the modal test (triggered hammer method) and issues of inaccuracy in measurements are raised and as discussed in previous chapters. Thus, findings conforming to the objectives of this study are listed as below:

1. Extended moist curing up to 58 days have the concrete beam demonstrated more consistent changes in natural frequency than that which was only cured for 28 days, when comparing final frequencies to initial frequencies;
2. Extended moist curing up to 58 days results in concrete beam with higher MAC value than that which was only cured for 28 days, thus showing better correlation between interested mode shape and the initial mode shapes of each mode, and;
3. Extended moist curing up to 58 days developed better concrete properties as well as modal parameters than that which was only cured for 28 days, as extended curing enhance further cement hydration and development of modal properties in young concrete.

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