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Developing Sustainable Concrete Compaction using a Proposed Multi-vibration Technique

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ABSTRACT

This study seeks to develop a sustainable construction technique based on the introduction of a specific method for improving concrete compressive strength through a proposed multi-vibration compaction method. An experimental program is performed to evaluate the effect of the proposed compaction technique on fresh silica fume concrete undergoing the initial setting. Multi-vibration intends to minimize concrete production cost because it upgrades the compressive strength of the same materials with better utilization of the vibration energy required for compaction. The collected experimental data presented assign relationships among vibration duration, vibration cycles or phases, and compressive strength upgrading of single vibrated, revibrated, and multi-vibrated specimens for analysis and discussion. This study shows that multi-vibration phases, rather than single vibration or revibration techniques, are powerful techniques for improving concrete compressive strength. The results indicated that the existence of an optimum multi-vibration mode was dominated by phase number and vibration duration and confirm the reliability vibration overall time duration recommended by ACI 309 which relates to a single vibration time limit to be considered in the case of multi vibration technique. Multi-vibration Mode 8 (subjected to three vibration phases 10, 20, and 30 sec) has the best effect for the considered mixtures among the specific vibration modes. The maximum improvement ratio is 1.25, which is associated with the plastic mixture.

1. Introduction

Sustainable construction is the creation and responsible management of a healthy built environment based on resource efficiency and ecological principles [1]. Hence, sustainable construction, which includes design, tendering, site planning, organized material selection, recycling, and waste minimization, could also be described as a subset of sustainable development [2-4]. A mass of freshly placed concrete is usually honeycombed with entrapped air. If allowed to harden in this condition, the concrete will be nonuniform, weak, porous, and poorly bonded to the reinforcement. It will also have a poor appearance. The mixture must be consolidated if it is to have the properties normally desired and expected of concrete [5]. Multi-vibration intends to minimize concrete production cost because it upgrades the compressive strength of the same used materials with better utilization of the vibration energy required for compaction. **Fig.1** shows the themes of sustainable development [6]. A researcher stated that the re-vibration technique can ensure strength improvement for the same liner concrete mix which in turn ensuring the cost effectiveness of the construction [7]. This research seeks to develop a sustainable construction technique based on introducing a specific compaction method to improve the compressive strength of concrete precast units through a proposed multi-vibration technique. Compaction is the technique of inducing optimal

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particle arrangement in mixed concrete or mortar, during casting, by reducing voids through vibration. By using chemical admixtures, consistencies requiring reduced compaction effort can be obtained with low water content to improve concrete quality provided that the mixtures are consolidated sufficiently. If the mixtures are compacted inadequately, the quality of the hardened concrete degrades drastically [5]. This research is an attempt to investigate the compressive strength of uniform, plastic, and highly plastic concrete made using silica fume as supplementary cementitious material for the partial replacement of cement. The replacement ratios in this study are 5%, 10%, and 20%. The benefits of silica fume as a material that could increase concrete strength can be maximized by using smart vibration modes in accordance with concrete workability. Ornowski [8] conducted a classical study on the effect of the continuous vibration of concrete. Many other works have focused on vibration and revibration as appropriate compaction processes and investigated various parameters [9-12]. However, these studies remain limited and have interested researchers in the present. Krishna and Rathish investigated the revibration effect on compressive strength and density with different w/c ratios, lag intervals, and revibration cycles [13]. Kassim examined the effects of revibration on retarded concrete compressive strength at late lag intervals based on initial and final setting times. Various time lag intervals and cement retardant dosages are also considered [14]. The multi-vibration concept is adopted to identify the relationship between vibration duration, vibration phase, and compressive strength upgrading of single vibrated, revibrated, and multi-vibrated specimens. The test results obtained will be reviewed to illustrate development during various vibration modes. This study confirmed that the multiphase and revibration technique is applicable as a powerful compaction method in concrete production. The multi-vibration technique may be a necessary and complementary step for concrete production. The optimum multi-vibration mode should be determined during trial batches.

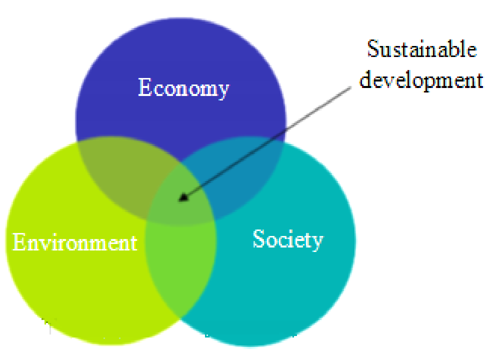


Figure. 1 Themes of sustainable development [6]

2. Experimental Investigation

2.1. Material Properties

The details of the constituent material properties are described below.

2.1.1. Binder Materials

Portland Cement

Portland cement (Type I) used in this work was manufactured by an Iraqi factory and was designated as Tasloga cement. It was stored in air-tight sheets to eliminate the effects of humidity. Physical property and chemical analysis indicated that the cement used is conformed to ASTM C150-04 [15].

Silica Fume

Mega Add MS (D), a micro silica fume [16] which conforms to the chemical and physical requirements of ASTM C1240-03 [17], was used throughout the current study. It is a new-generation concrete additive in gray powder form, is a by-product of highly active pozzolanic material, and is ready to be used. This fume was used at 5%–20% by mass of cementitious materials as partial replacement for concrete structures that require high strength or considerably reduced water permeability [18].

2.1.2. Fine and Coarse Aggregates

Locally available natural sand with smooth texture, round particles with a maximum size of 4.75 mm, and yellowish-brown color were used for concrete batches. The used fine aggregates conformed to the Iraqi specification No. 45/1984[19], ASTM C33-03[20], and B.S. 882:1992[21]. Locally available washed crushed coarse gravel with a maximum size of 18 mm was used. Its grading was within the Iraqi specification requirements No. 45/1984[19]. Various dosages of silica fume that are 0.5%, 10%, and 20% (designated as A, B, and C groups respectively) were adopted. Plastic, highly plastic, and uniform mixtures were used (slump; 60, 90, and 110 mm) to control the workability effect of fresh concrete. This is an important consideration in the selection of the compaction method for concrete precast production[5]. The material proportions of the investigated sets are listed in **Table 1**. Concrete mixtures are proportioned to provide the workability needed during construction and the required properties in the hardened concrete. **The** prepared samples, used in the present study, were divided into three batches. In each batch, one sample was used as a reference specimen. The adopted mixing procedure is according to ASTM specification C305-65 [22] for mixing mortars.

All batches were mixed in a 0.5 cubic meter capacity portable mixer. Specimens with dimensions of 100 mm × 100 mm × 100 mm were used [23]. They were cured in a moist curing pool. A hydraulic, 2000-ton capacity, compressive testing device was used in this study; the testing load was applied monotonically in increments (rate of loading about 10 kg/sec). The increments were decreased as the load reaches the failure load. An ultrasonic and schmited hammer was employed to confirm the predicted results as shown in Plate 1.

3. Vibration Procedure

The vibration consists of subjecting freshly placed concrete to rapid vibratory impulses which liquefy the mortar and drastically reduce the internal friction between aggregate particles. While in this condition, concrete settles under the action of gravity (sometimes aided by other forces). When vibration is discontinued, friction is re-established.

A vibrating table normally consists of a steel or reinforced concrete table with external vibrators rigidly mounted to the supporting. The table and the frame are isolated from the base by steel springs, neoprene isolation pads, or other means.

The electrical asynchronous motor table vibrator model Type VV03N/2 [24] shown in plate 2 was used. In the model, two ends of the shaft were enhanced with different weights. The details of the specific features of the vibrator that make it suitable for use are shown in **Table 2.**

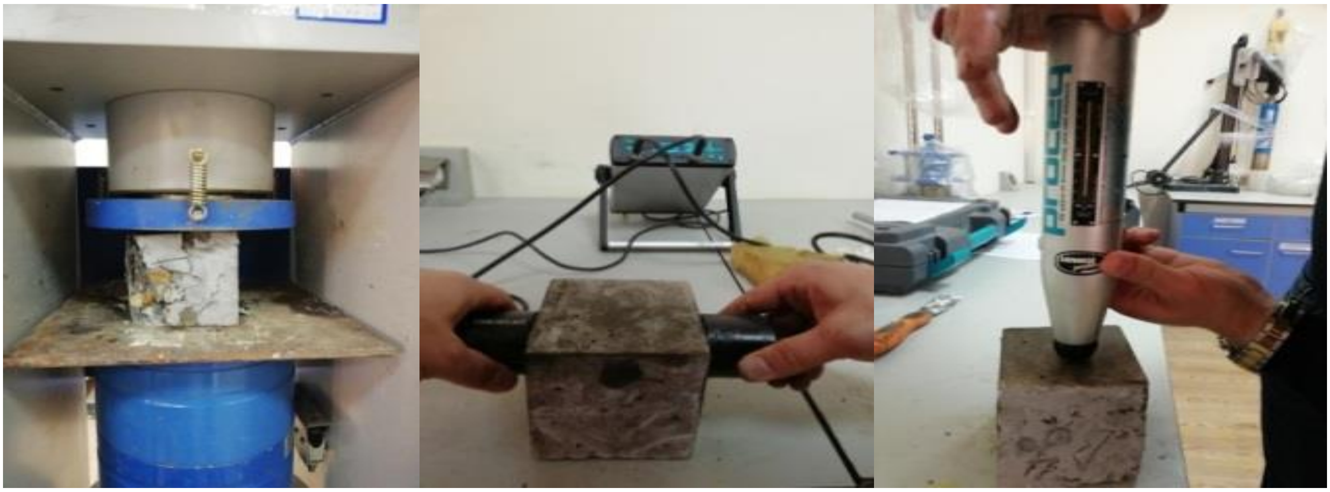


Plate 1. Test settings

Table 1. Experimental methodology

No.	Mix Type	Cement kg/m^3	Silica fume kg/m^3	binder kg/m^3	Sand kg/m^3	Gravel* (kg/m^3)	water (kg/m^3)	W/Binder (%)	Superplastizer (kg/m^3)	Superplastizer/ Binder P/B (%)	Silica/Binder, S/B (%)	Binder:Sand: Gravel	Slump (mm)	Mixture Workability **
1	A	784	41.3	825	1031	1650	330	40	8.25	0.1	5	1:1.25:2.0	110	uniform
2	B	792	88	880	1100	1760	352	40	8.8	0.1	10	1:1.25:2.0	90	plastic
3	C	704	176	880	1100	1760	440	50	8.8	0.1	20	1:1.25:2.0	63	high plastic

Table 2. Electrical motor shaking table characteristics

Type	VV03N/2
Maximum centrifugal force in kN	1.18
Power source voltage rating in Volts	230/400
Maximum current rating in Amperes	0.57/0.33
Rotation speed in revolutions per minute (RPM)	3000
Rated power, output power, in kW	0.17
Power source frequency rating (Hz)	50
Phase angle of the electric motor	0.74
Max. amb.	40
Weight (kg)	5.8

Plate 2. Vibration table (Model VV03N/2)

Nine vibration modes were used. These modes varied in terms of vibration cycles or phases and duration. Samples were subjected to different cycles of vibration, whereas control specimens were consolidated only once. Other samples were subjected to two or three vibration phases. Two approaches were considered to determine the duration of each vibration iteration. The first approach was based on the acceptable limit (20 s) set by ACI 308, whereas the second approach was based on an extreme duration (60 s). The period between successive vibration phases was 20 min. **Fig. 2** illustrates the phase number and duration time of each vibration mode, **Table 3** explains the Specimen's description concerning vibration duration.

No.	Group	Vibration Mode	Specimen sets	Vibration time (sec) 1st Phase	2nd Phase	3rd Phase	accumulative time
1	A	Mode (1)	A1	60	-	-	60
2		Mode (5)	A2	20	-	-	20
3		Mode (6)	A3	20	20	-	40
4		Mode (7)	A4	20	20	20	60
5		Mode (8)	A5	10	20	30	60
6		Mode (9)	A6	30	20	10	60
7	B	Mode (1)	B1/1	60	-	-	60
8		Mode (2)	B1/2	60	60	-	120
9		Mode (3)	B1/3	60	60	60	180
10		Mode (4)	B1/4	60	40	20	120
11		Mode (5)	B2	20	-	-	20
12		Mode (6)	B3	20	20	-	40
13		Mode (7)	B4	20	20	20	60
14		Mode (8)	B5	10	20	30	60
15		Mode (9)	B6	30	20	10	60
16	C	Mode (1)	C1/1	60	-	-	60
17		Mode (2)	C1/2	60	60	-	120
18		Mode (3)	C1/3	60	60	60	180
19		Mode (4)	C1/4	60	40	20	120
20		Mode (5)	C2	20	-	-	20
21		Mode (6)	C3	20	20	-	40
22		Mode (7)	C4	20	20	20	60
23		Mode (8)	C5	10	20	30	60
24		Mode (9)	C6	30	20	10	60

Note: time between success phases is 20 min

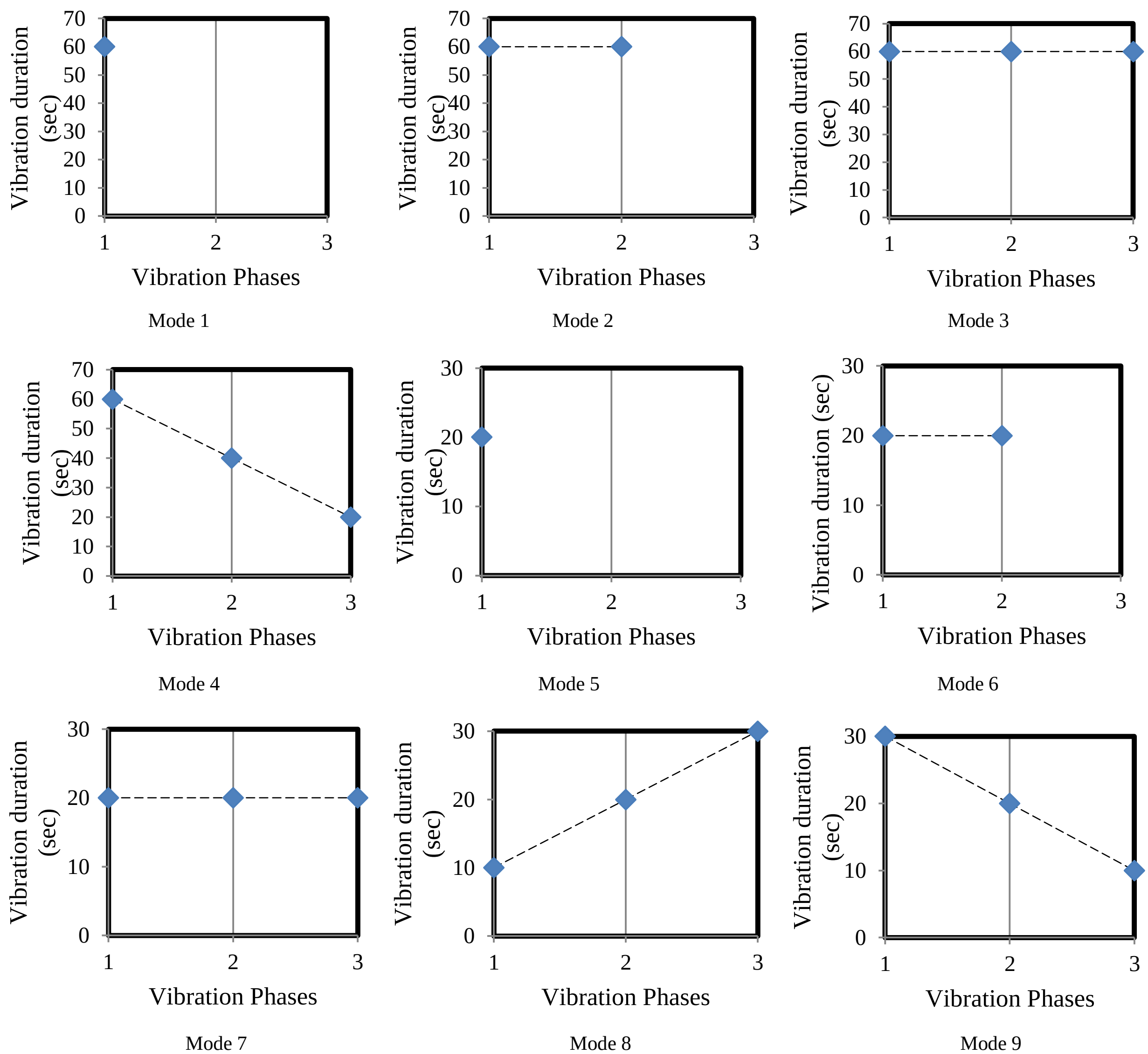


Figure 2. Phase number and duration time of each vibration mode

Fig. 3 depicts the vibration mode durations and cumulative durations for all specimen sets subjected to one and/or two and/or three phases of vibration.

4. Results and Discussion

The results presented in **Table 4** show the phase sequence of the vibration process is rather important than the cumulative vibration duration. This can be seen clearly in the results of the control mode of compressive strength compared with other modes achieved with different vibration phases.

The results for the tested specimens are presented in **Tables 4-6**. Each table presents comparisons with assigned controlled specimens. **Table 4** shows that the supplementary vibration energy effects are varied within customary limits according to the ACI 309 committee. Specimens of unique vibration phases are assigned within different groups as controlled specimens and are vibrated for 20 sec only (A2, B2, and C2).

The assigned specimens are referred to under revibration and multi-vibration phases of the average time (20 sec) and various accumulative times (various vibration energy). Specimens in different groups vibrated under mode 8 exhibited high strength upgrading with a maximum improvement ratio of 1.25, which is associated with the high plastic mixture. Such a low flowability degree is the result of the optimum cement water ratio in the mixture. The mixture is more stable with minimized segregation during the compaction process.

Table 5 shows that different specimens subjected to the same supplementary vibration energy were considered. Also, the specimens subjected to 60 s of vibration time were designated as the control specimens (A1, B1/1, and C1/1) to be referenced to those subjected to revibration and multi-vibration for a cumulative duration of 60 s (supplementary vibration energy is equal). The same previous vibration mode (Mode 8) produced specimens with high strength upgrading ratio. The best improvement was observed in the mixture of uniform consistency (A). This mixture contains micro bubbles since the further agitation of the mixture by sustainable vibration process caused small entrapped air bubbles to rise to the surface while large air bubbles are more easily removed during the early vibration process than small ones because of their greater buoyancy**.** The strength of this specimen increased to 1.222, which exceeded 1.125 for the same specimen (A5) in **Table 4** for the variable supplementary vibration energy of specimens under the 20 s single-phase vibration time. As inferred from the results in **Tables 4 and 5**, although the cumulative vibration time was 60 s, the strength upgrading differed, thereby reflecting the effect of multi-vibration phases.

Table 6 shows the effects of extreme supplemental vibration energy. It provides a comparison of the specimens subjected to revibration and multi-vibration phases with an average duration of 60 s and different cumulative vibration times (60–180 s) with control specimens subjected to an extremely unique vibration phase for 60 s (B1/1, and C1/).

The comparison of the strength upgrading of control specimens with that of specimens subjected to various supplemental vibration energies within customary limits according to ACI 309 is shown in **Table 4**. The table indicates that the slight increase in compressive strength was because of the extreme vibration in different modes, which was useless in terms of supplementary vibration energy, this finding confirms the negative effect of over vibrating and could be contributed to getting undesirable deformation in initial bonding of early developed cementitious gels.

Fig. 4 illustrates the comparison among the effects of single, revibration, and multi-vibration phases on the tested sets. The strength of the specimens subjected to the powerful three-phase multi-vibration mode for 20 s per phase, which was within the recommended vibration duration limits of ACI 309, increased by 1.074, 1.088, and 1.1 relative to those of the specimens subjected to a single vibration mode for the B, A, and C series as shown in **Fig. 6-a**. These results confirm the reliability vibration time duration recommended by ACI 309 which relates to a single vibration time limit to be considered in the case of multi vibration technique. The strength upgrading ratios of the specimens subjected to revibration with a regime duration of 60 s were 1.134 and 1.129 with respect to those of the specimens subjected to the single vibration mode for the B and C series, respectively. This observation confirmed that for long vibration duration two phases vibration of two iterations assigned as a more efficient technique than three phases -vibration compaction, as shown in **Fig. 6-b.**

Table 4. Comparison of revibration and multi-vibration phases with an average duration of 20 s and different cumulative times with a single phase of 20 sec

No.	Specimen sets	Vibration Mode	Vibration Phase order	Average time of vibration phase (sec)	Accumulative time of all phases	f_{cu} (MPa)	f_{cu}* (Compressive strength of control specimen, MPa)	Rg = f_{cu}/f_{cu}*
2	A2	Mode (5)	1	20	20	58.2		1.00
3	A3	Mode (6)	2	20	40	60.8		1.05
4	A4	Mode (7)	3	20	60	63.3	A2= 58.2	1.09
5	A5	Mode (8)	3	20	60	65.5		1.13
6	A6	Mode (9)	3	20	60	61.5		1.06
11	B2	Mode (5)	1	20	20	60.3		1.00
12	B3	Mode (6)	2	20	40	63		1.05
13	B4	Mode (7)	3	20	60	64.7	B2= 60.3	1.07
14	B5	Mode (8)	3	20	60	66.7		1.11
15	B6	Mode (9)	3	20	60	63.3		1.05
20	C2	Mode (5)	1	20	20	53.8		1.00
21	C3	Mode (6)	2	20	40	56		1.04
22	C4	Mode (7)	3	20	60	59.2	C2=53.8	1.10
23	C5	Mode (8)	3	20	60	60.6		1.13
24	C6	Mode (9)	3	20	60	59.5		1.11

Table 5. Comparison of revibration and multi-vibration phases with an average duration of 20 s (constant accumulative time, 60 s) with respect to a single phase of 60 s

No.	Specimen sets	Vibration Mode	Vibration Phase order	Average time of vibration phase (sec)	Accumulative time of all phases	f_{cu} (MPa)	f_{cu}* (Compressive strength of control specimen, MPa)	Rg = f_{cu}/f_{cu}*
1	A1	Mode (1)	1	60	60	53.6		1.00
4	A4	Mode (7)	3	20	60	63.3	A1= 53.6	1.18
5	A5	Mode (8)	3	20	60	65.5		1.22
6	A6	Mode (9)	3	20	60	61.5		1.15
2	B1/1	Mode (1)	1	60	60	61.7		1.00
13	B4	Mode (7)	3	20	60	64.7	B1/1=61.7	1.05
14	B5	Mode (8)	3	20	60	66.7		1.08
15	B6	Mode (9)	3	20	60	63.3		1.03
6	C1/1	Mode (1)	1	60	60	53.1		1.00
22	C4	Mode (7)	3	20	60	59.2	C1/1=53.1	1.11
23	C5	Mode (8)	3	20	60	60.6		1.14
24	C6	Mode (9)	3	20	60	59.5		1.12

Table 6. Comparison of revibration and multi-vibration phases with average durations of 60 s (various cumulative time with respect to a single phase of 60 s)

No.	Specimen sets	Vibration Mode	Vibration phase order	Average time of vibration phase (sec)	Accumulative time of all phases	f_{cu} (MPa)	f_{cu}* (Compressive strength of control specimen, MPa)	Rg= f_{cu}/f_{cu}*
1	B1/1	Mode (1)	1	60	60	61.7	B1/1= 61.7	1
2	B1/2	Mode (2)	2	60	120	70		1.13
3	B1/3	Mode (3)	3	60	180	62.3		1.01
4	B1/4	Mode (4)	3	40	120	66.7		1.08
5	C1/1	Mode (1)	1	60	60	53.1	C1/1= 53.1	1
6	C1/2	Mode (2)	2	60	120	60		1.13
7	C1/3	Mode (3)	3	60	180	56.7		1.07
8	C1/4	Mode (4)	3	40	120	55.4		1.04

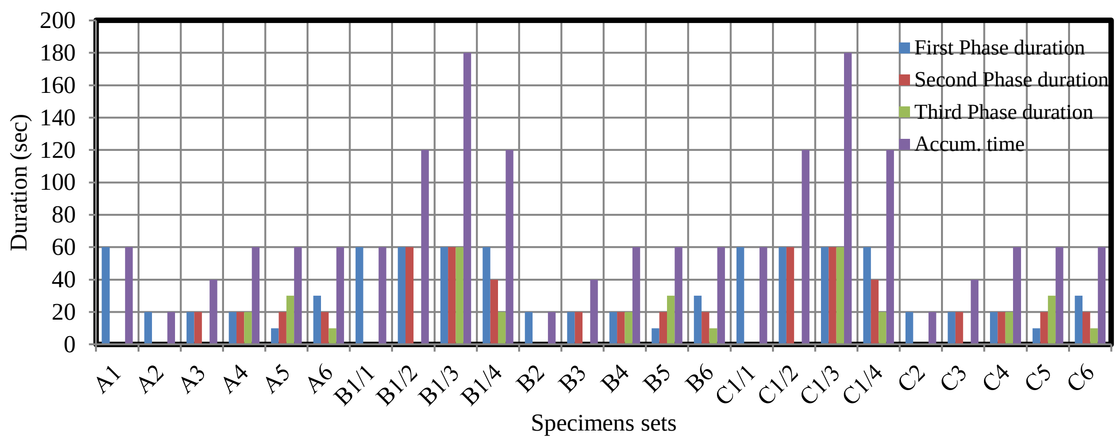


Figure 3. Vibration mode durations and cumulative durations for all

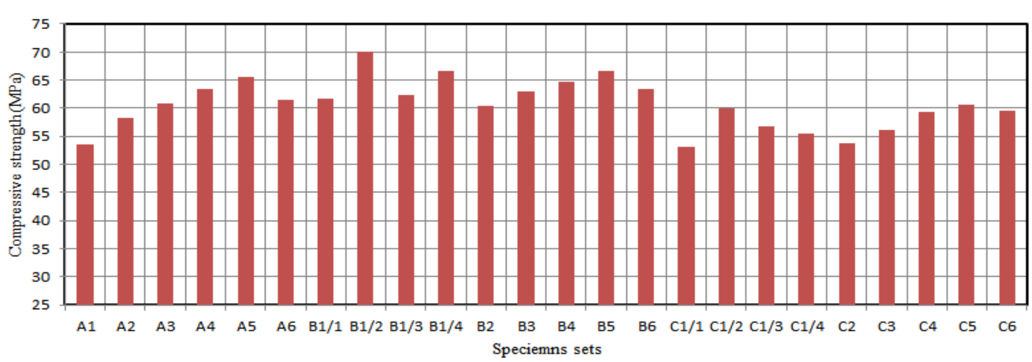


Figure 4. Variations in the compressive strength of specimen sets in all vibration modes

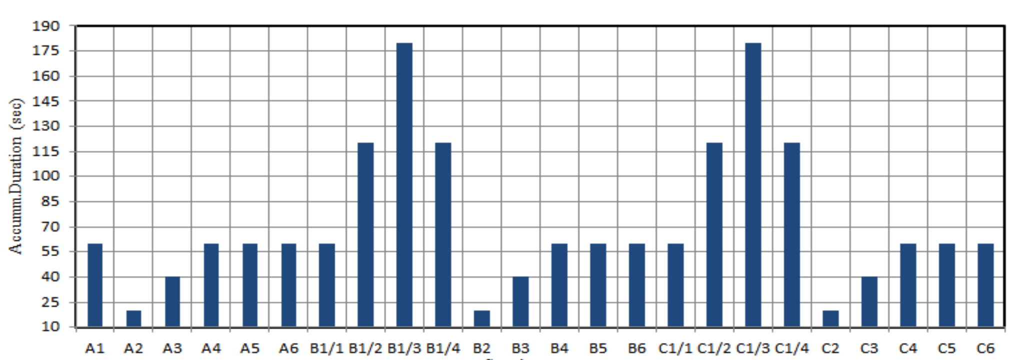
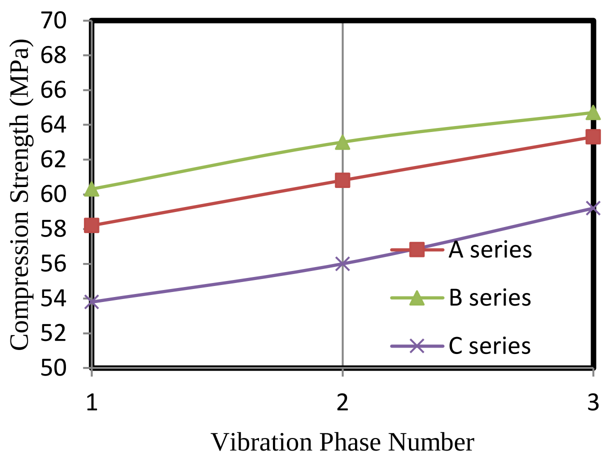
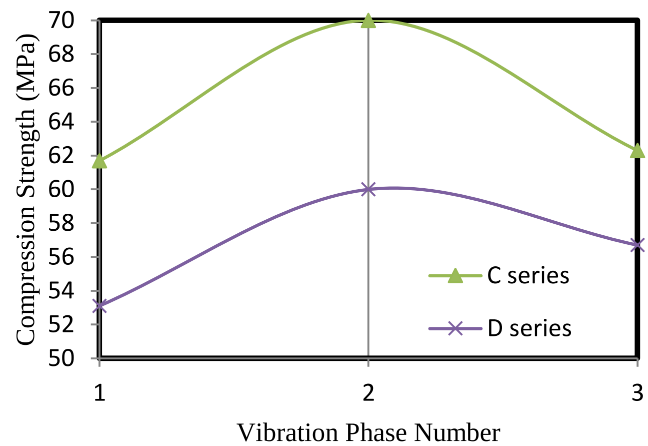


Figure 5. Variations in the cumulative applied vibration time of all specimen sets in all vibration modes





a. (Vibration phase time = 20 s) **b. (Vibration phase time = 60 s)**

Figure 6. Effects of single, revibration, and multiphase vibration on compressive strength

Figs. 6 and 7 illustrate the effect of the interaction of the silica fume with the vibration response on the admixture compressive strength and mixture workability. The figures show that strength decreased when a high silica fume ratio (20%) was adopted and mixture workability tended to be plastic consistency.

The constant supplementary vibration energy was verified in **Fig.7**, which shows the effect of silica fume ratio on compressive strength under vibration modes of equal overall cumulative vibration time (60 s) but different phases (10, 20, and 30) with an average duration of 20 s. Specimens with 10% silica fume were characterized by a mixture of plastic workability and were highly responsive to different vibration modes, with Mode 8 presenting high effectiveness and its compressive strength increased to 66.7 MPa from 61.7 MPa under the single vibration mode (Mode 1).

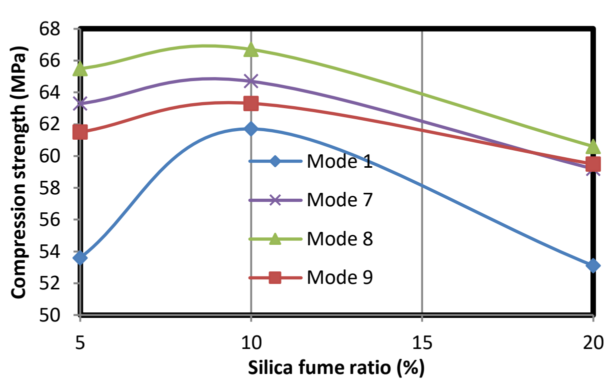


Figure 7. Relationship of silica fume ratio and compressive strength on vibration modes with constant cumulative vibration time and different phase periods

The effects of single, revibration and multi-vibration modes (Modes 5, 6, and 7) on a series of specimens with different silica fume ratios (5%, 10%, and 20%) are illustrated in **Fig. 8**. The multi-vibration mode (Mode 7) had a stronger effect than the revibration mode (Mode 6). **Fig. 8** shows the 10% silica fume ratio was the ratio with the best compatibility with the three-phase multi-vibration mode. This observation could be related to the consistency improving in present of silica particles.

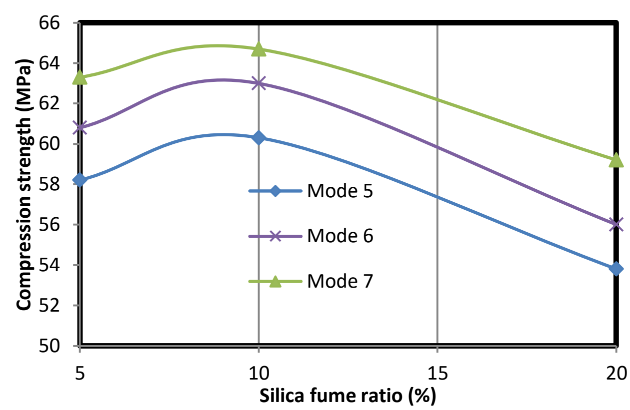


Figure 8. Relationship of silica fume ratio and compressive strength under single, revibration, and multi-vibration modes

Fig. 9 shows the improvements in the concrete strength of all tested groups as a function of different vibration modes. This improvement could be ordered as Modes 8, 7, and 9 in accordance with the efficiency of strength upgrading. Among these modes, Mode 8, which involved three steps of vibration with linearly tapered phase time increments (10, 20, and 30 s), was the best.

The macro views of intersections in the specimens were obtained. The equivalent radii of voids within concrete particle structures ranged between 40 and 88 μm and were 55 μm on average. The main objective of vibration, re-vibration, and multi-vibration is to expulsion of air bubbles out of the concrete matrix. in fact, this process can mitigate the voids in the microstructure of concrete and increases the density of concrete. A researcher stated that the re-vibration enhanced the compressive strength and increases the density [7]. A typical view is provided in a plate (3). Plate (4) illustrates the concrete surface texture within specimens from various groups in compaction under Mode 5 to those under the unique vibration phase (Mode 1). The concrete surface texture and overview surface color changed as a function of the silica fume ratio.

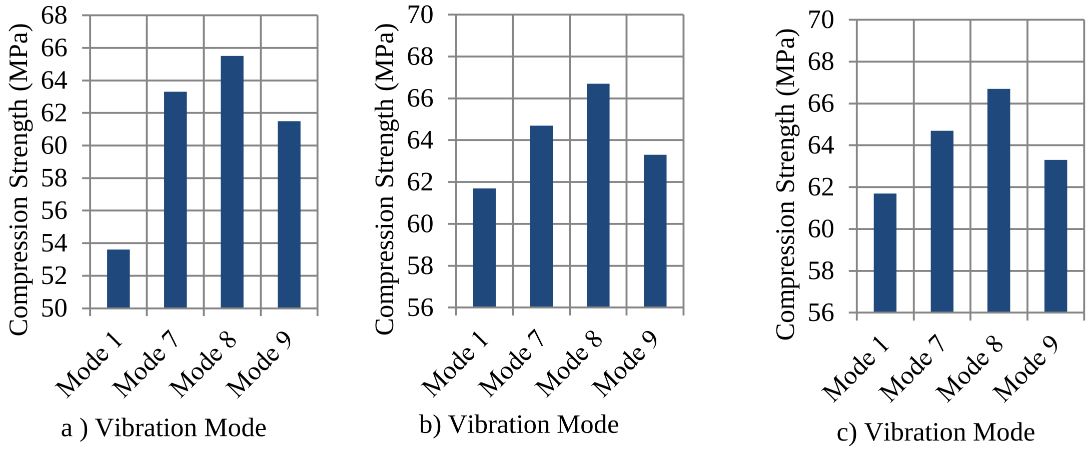


Figure 9. Effects of vibration modes on the compression strength of different groups (A, B, and C)

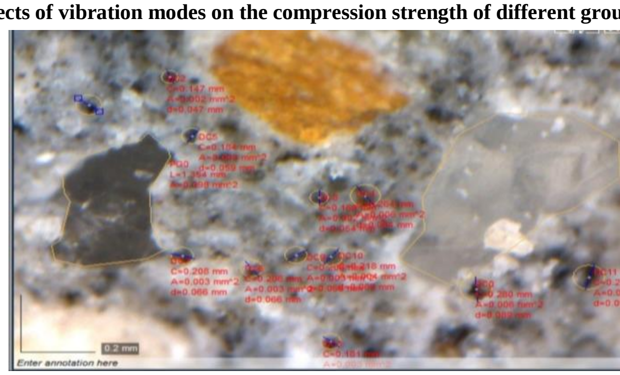
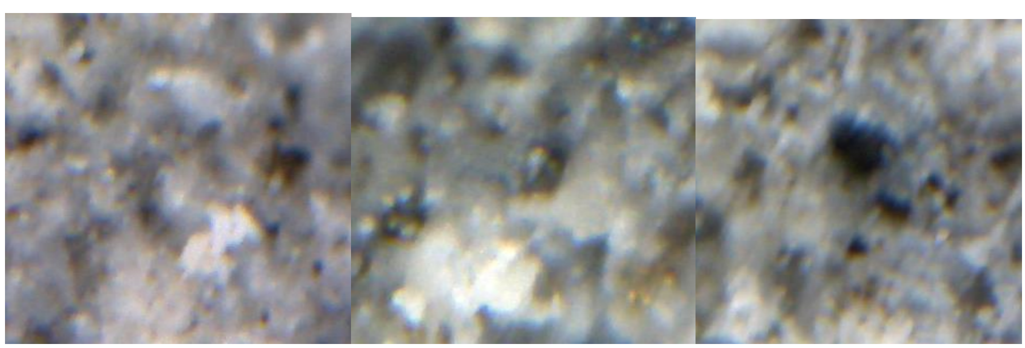
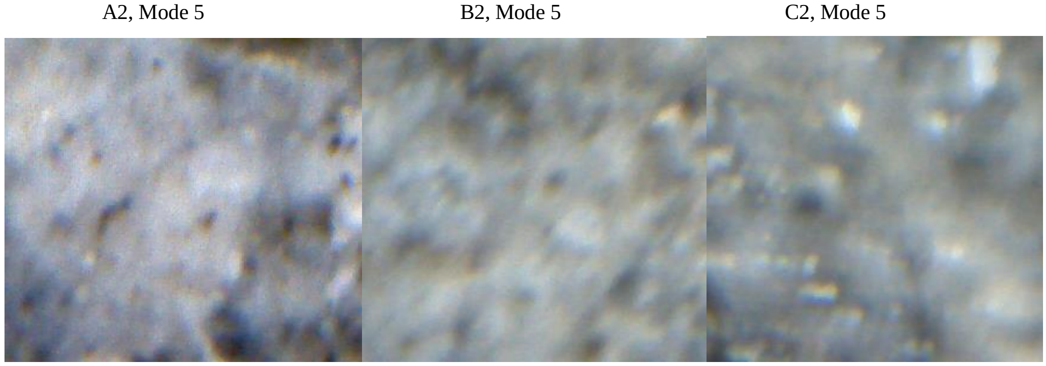


Plate 3. Typical laminated view of a differential area of 0.04 mm, specimens B5



A2, Mode 5 B2, Mode 5 C2, Mode 5



B5, Mode 8 C5, Mode 8 D5, Mode 8

Plate 4 Concrete surface texture within an elementary differential area of 0.0004 mm2 of various tested groups under Mode 8 in comparison with those under unique vibration phase (Mode 5)

5. Conclusion

1. The multiphase and revibration technique is confirmed to be an applicable powerful compaction method in concrete production.
2. An optimum multi-vibration mode dominated by phase number and vibration duration existence.
3. The optimum multi-vibration mode could be determined during trial batches.
4. Concrete specimens with uniform, plastic, and high-plastic workability have different sensitivities to vibration, and plastic mixture has increased response.
5. Among the specific vibration modes in this study, the multi-vibration Mode designated as Mode 8 has the best effect on the considered mixtures. The maximum improvement ratio is 1.25, which is associated with the plastic mixture.
6. The automation of vibration energy consumption is dependent on the duration and phase number of the vibration mode and could be performed as a necessary and complementary step of precast concrete production.
7. The strength upgrading of specimens vibrated in different modes with constant cumulative vibration time differs and thus reflects the effect of the multi-vibration phase.
8. The rational and low increase in compressive strength could be attributed to extreme vibration in different modes and is useless for supplementary vibration energy.
9. The results confirm the reliability vibration overall time duration recommended by ACI 309 which relates to single vibration time limit to be considered in the case of multi vibration technique.
10. Revibration processes are more efficient than the multi-vibration phase for specimens subjected to vibration regime duration of 60 s. The average strength upgrading ratio was 1.13.
11. The interaction effect of silica fume presence on the compressive strength as enhancing admixture agent and on mixture workability vibration response could be beyond strength reduction of specimens with high silica fume ratios (20%). Specimens with 10% silica fume are characterized by a mixture of plastic workability and positive response to different vibration modes.

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