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Effect of Vacuum Intrusion Compaction on the Mechanical Properties of Mortar

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Abstract. The Vacuum Intrusion Compaction Method (VICM) can be defined as a mortar or cement based material compaction method which applies the principle of air pressure in extracting air bubbles trapped in mortar in order to achieve the objective of compaction. This alternative compaction method is able to prevent segregation from happening in mortar and other cement based materials. It also provides better control over the orientation of the elements inside the mortar. Laboratory tests on the physical and mechanical properties of mortars were conducted to study bulk density, porosity, compressive strength, and flexural strength in the early stages of strength development of different mortars. Through such testing, the effectiveness of the vacuum intrusion method on the effect of compaction could be observed. The outcome of this research shows that the VICM is capable of compacting mortar and extracting macro pores, thereby providing a relatively similar compressive strength and flexural strength to that of the standard compaction method. However, it is not efficient in extracting micro pores, therefore, leading to high porosity of the mortar specimens. As a conclusion, the vibration compaction method is still considered a good compaction method when compared to VICM.

1 Introduction

A building is composed of different types of artificial materials such as concrete, brick, mortar, and so on. These building materials are made up of a certain volume of empty spaces in the form of pores, cavities, and capillaries which occur in a variety of different shapes and sizes [1]. These voids play a very vital role in structural performance since their volume, size and distribution can greatly influence their behaviours under different surrounding environments, i.e. the effects of weather in aggressive environments [2]. Since water is the main component to which building materials exposed, open pores and micro-cracks have considerable effects on the fluid storage and circulation capacity within the building materials and, therefore, inevitably lead to deterioration and lowering of mechanical resistance. The transport of water between bricks and mortar can also influence the quality of the interface.

The main factor which causes high porosity and the existence of pores in the first place in cement-based construction materials is an insufficient degree of compaction. Vibration is the conventional method of compaction. Through suitable degrees of vibration, the components inside the mortar can be better oriented and more closely interconnected. However, excessive amounts of vibration will cause heavier particles in the mortar to sink to the bottom, whereas water and other low density components will float up to the surface. This phenomenon is called segregation and it can seriously affect the mechanical performance of the mortar. In order to prevent insufficient compaction which causes high porosity and over vibration which will further lead to segregation in mortar, this research introduces the Vacuum Intrusion Compaction Method (VICM) as an alternative method.

2 Materials

2.1 Portland Cement:

Portland cement is the binder in mortar as it holds the solid particles together in a coherent mass [3]. It must possess several important physical properties such as a specific gravity of 3.06 and Blaine fineness of $2888cm^2/g$. The use of Portland cement in this research conformed to ASTM C150, Standard Specifications for Portland cement [4].

2.2 Fine Aggregates

An aggregate can be defined as the granular material which is not involved in the chemical reaction and hardening process of mortar. It is one type of component in the material that mortar is made of and is un-reactive, filling up approximately 75% of the volume of the mortar. The fine aggregate which was used in this research was river sand of 4.75mm in diameter. Table 1 shows the properties of the fine aggregate in this research.

Table 1. Properties of fine aggregate

Property	Determined as
Apparent Specific Gravity	2.50
Dry Specific Gravity	2.36
Saturated Surface Dry (SSD) Specific Gravity	2.41
Absorption	2.41

2.3 Super Plasticizer

An additive is an organic or inorganic material that is added in small quantities to modify the properties of fresh mixed mortar or mortar after the hardening process. Super plasticizer is one type of water-reducing admixture. It is effective in controlling the amount of water which is required for fabricating fresh mortar. In this research, it was mainly used to achieve the same level of workability by decreasing the water to cement ratio.

3 Experimental Method and Setup

The ratio of the ingredients in mortar is 1:2 (cement:sand) with water content of 0.4. In this research, the amount of materials required for fabrication was determined by using the Absolute Volume Method:-

$$x / (3020 \text{ kg/m3}) + 2.2x / (2830\text{kg/m3}) + 0.4x / (1000\text{kg/m3}) = 1$$

Where,

Specific Density of Cement:	$3020kg/m^3$
Specific Density of Fine Aggregate:	$2830kg/m^3$
Density of Water:	$1000kg/m^3$
Workability requirement in flow table test:	150mm – 160mm

In order to achieve this workability requirement of a ratio of 0.4 parts water to one part cement, super plasticizer was added. The amount of super plasticizer added was 2% binder of mortar, which is known as cement. The addition of super plasticizer was carried out in a gradual manner in increments of 0.2% until the required workability was achieved.

There were 3 different sizes of specimens used in this research which were cubes with dimensions of 50 mm in length, 50 mm in width, and 50 mm in height; prisms with dimensions of 160mm in length, 40mm in width and 40mm in height; and cylinders with dimensions of 50mm in length and 50mm in diameter. These specimens were prepared to undergo 3 different types of compaction methods which were vibration for 15 seconds followed by 10 minutes of the Vacuum Intrusion Compaction Method (VICM), vibratory compaction only and VICM only. Afterwards, these specimens were cured in water. At 7 days, 14 days, 21 days and 28 days of curing, the samples were tested to determine their bulk density, porosity, compressive strength, and flexural strength.

4. Results and Discussion

4.1 Bulk Density

The average results for bulk density recorded by all specimens at 7, 14, 21 and 28 days of curing are presented in Table 2. The mean bulk density of the vibration compacted specimens was 2.27gcm^{-3} on the 28th day of curing. This method demonstrated a higher bulk density than the other two types of compaction methods which were vibration followed by VICM (2.09gcm^{-3}) and VICM only (2.08gcm^{-3}). A valid explanation for this situation is that the vibration compaction method is a more efficient compaction method which makes the density of specimens higher along with a low portion of empty spaces.

Table 2. Mean bulk density of specimens compacted with different compaction methods at 7, 14, 21, and 28 days of curing.

Compression Method	Mean Bulk Density at 7 days (gcm^{-3})	Mean Bulk Density at 14 days (gcm^{-3})	Mean Bulk Density at 21 days (gcm^{-3})	Mean Bulk Density at 28 days (gcm^{-3})
Vibration + VICM	2.00	2.02	2.04	2.09
Vibration only	2.26	2.26	2.26	2.27
VICM only	1.79	2.03	2.02	2.08

Table 3 shows that the mean bulk density of all the specimens fell in the range of 2000kg.m^3 to 2280kg.m^3. Therefore, the mortar fabricated in this research can be categorized as a normal weight mortar.

Table 3. Mean and Standard Deviation for the bulk density of all fabricated mortar specimens over the course of 4 weeks

Compaction Method	Mean (gcm^{-3})	Standard Deviation (gcm^{-3})
Vibration + VICM	2.085	0.0125
Vibration only	2.270	0.0062
VICM only	2.080	0.0068

Figure 1 shows that the mean bulk density of all specimens increased as the curing age of the mortar increased. This is because hydration in the cement took place with an adequate supply of water to form a more compacted microstructure.

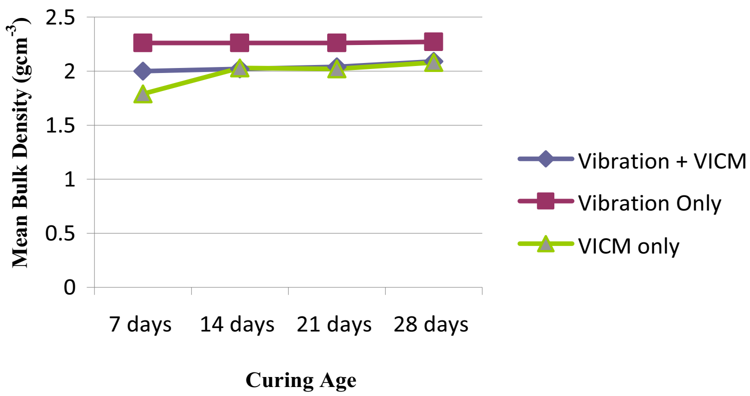

Figure 1 Development of Mean Bulk Density of specimens over 4 weeks with different methods of compaction.

4.2 Compressive Strength

The mean and average results for compressive strength for all the specimens at 7, 14, 21, and 28 days of curing are illustrated in Table 4.

Table 4 shows that the specimens compacted by only vibration achieved the highest compressive strength of 38.03MPa on the 28th day of curing, whereas the average compressive strength of the specimens which were compacted by VICM was slightly lower at 32.04MPa. The lowest mean compressive strength at 28 days of curing was 23.59MPa by the specimens' compacted using vibration for 15 seconds, followed by 10 minutes of Vacuum Intrusion Compaction.

Based on the differences in the compressive strengths of the samples, the most effective compaction method was the vibration compaction method which gave the highest compressive strength to the mortar. Additionally, the VICM can also be considered an effective compaction method because it provided a compressive strength to the mortar of up to 84.25% in comparison to the vibratory compaction method with only 10 minutes of vacuum suction. However, the combination of both compaction methods did not provide a better compressive strength, but rather, a lower one.

One possible explanation for these results is that the VICM is only efficient in the extraction of macro pores but not when it comes to micro pores. When the mortar is freshly fabricated and has high workability, it is very beneficial to employ the VICM to extract the voids and air bubbles from the mortar. However, if the mortar has already been compacted by vigorous vibration, the majority of the macro pores will have already been extracted from the specimens and the particles in the specimens will be more firmly held together with each other. The micro pores need a longer time to escape from the mortar since the particles are firmly held together by vigorous vibration. In this research, the micro pores could not escape to the surface of the mortar within 10 minutes of vacuum suctioning. When this mortar underwent the VICM, the micro pores in the mortar raised up and concentrated near the surface, causing the area near the surface of the mortar to become very porous, thereby hindering the compressive strength.

Other than providing high compressive strength to the mortar, strength development of the mortar is another important indicator of the effectiveness of the compaction method. Figure 2 below outlines the compressive strength development of specimens through a graphical format.

Table 4. Results of breaking load and compressive strength for all specimens compacted with different compaction methods at 7, 14, 21, and 28 days of curing

Compaction Method		Average Strength on 7 days	Average Strength on 14 days	Average Strength on 21 days	Average Strength on 28 days
Vibrate + VICM	Breaking Load	41,594.3 N	45,448.7 N	52,913.3 N	58,977.21 N
	Stress	16.64MPa	18.18MPa	21.17MPa	23.59MPa
Vibrate Only	Breaking Load	73,115.7 N	79,216.7 N	95,933.27 N	95,063.83 N
	Stress	29.25MPa	31.69MPa	38.37MPa	38.03MPa
VICM Only	Breaking Load	53,611.33 N	56,390.27 N	81,294.65 N	80,109.57 N
	Stress	21.44MPa	22.52MPa	32.52MPa	32.04MPa

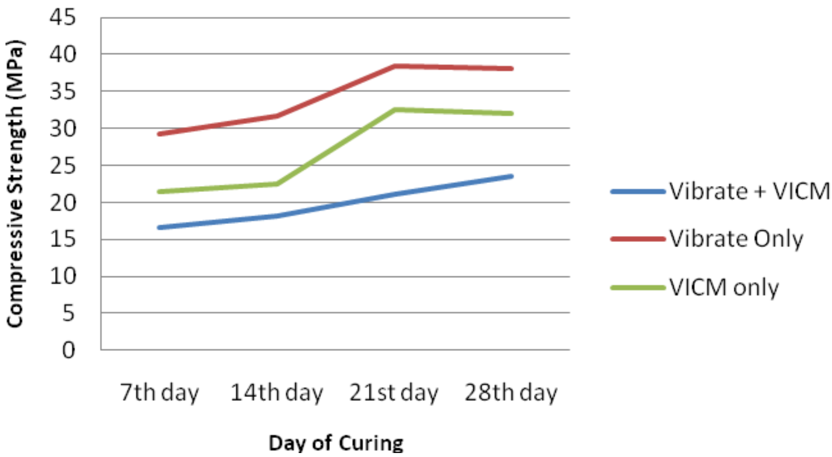

Figure 2. Development of compressive strength of the specimens compacted with different compaction methods over the course of 4 weeks.

The compressive strengths of all the specimens increased as the curing period was extended. The reason for this is because the reaction of carbonation was continuously carried out in the specimens during the curing process and crystal structures then formed and filled up the pores in the specimens. These crystal structures in the mortar can contribute to the compressive strength of the specimen. At 28 days of curing, the specimens treated with the VICM only or the vibratory compaction method only showed a slight decrease in compressive strength. This slight decrease in compressive strength indicated that the strength development had reached its maximum level and then started to slow down, eventually halting any further noteworthy development in compressive strength.

4.3 Flexural Strength Test

Flexural strength is one of the important indicators of the tensile strength of mortar. The mean values of flexural strengths for specimens at 7, 14, 21 and 28 days of curing have been tabulated in Table 5.

Table 5. Flexural strength of specimens treated with different methods of compaction at 7, 14, 21, and 28 days of curing

Compaction Method		Average Strength at 7 days	Average Strength at 14 days	Average Strength at 21 days	Average Strength at 28 days
Vibrate + VICM	Breaking Load	1543.15N	1602.83N	1622.5N	1645.1N
	Stress	4.34MPa	4.51MPa	4.56MPa	4.63MPa
Vibrate Only	Breaking Load	1953.8N	1861.0N	1987.03N	1995.33N
	Stress	5.495MPa	5.234MPa	5.589MPa	5.612MPa
VICM Only	Breaking Load	1782.55N	1861.67N	2021.97N	2032.77N
	Stress	5.013MPa	5.236MPa	5.687MPa	5.717MPa

In the beginning stages of the curing process, the specimens compacted with only the vibratory compaction method demonstrated a high mean flexural strength of 5.495MPa, whereas the second highest flexural strength (5.013MPa) came from the specimens compacted with only Vacuum Intrusion Compaction (VICM). This was followed by the specimens treated with the combination of both compaction methods with a recording of 4.34MPa.

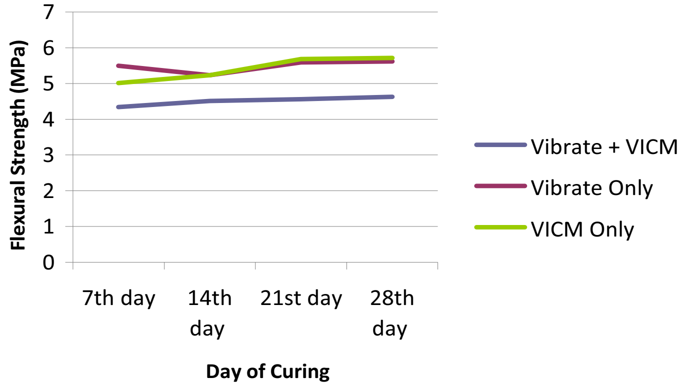

Figure 3. Development of flexural strength of the specimens as affected by different compaction methods over the course of 4 weeks.

However, the specimens treated with only the VICM showed the highest flexural strength of 5.236MPa and they took the lead on the following testing days. At 28 days of curing, the specimens treated with only the VICM showed the highest flexural strength among the rest with a reading of 5.579MPa. This figure was about 6.35% higher than the flexural strengths of the specimens treated with only vibration as well as the combination of both compaction methods which had recordings of 5.246MPa and 4.63MPa, respectively.

In Figure 3, it can be seen that there was a small drop in flexural strength for the specimens that underwent vibration compaction only and VICM only from 21 days to 28 days of curing. Flexural strength on the 21st day of curing was slightly lower compared to the flexural strength on the 28th day of curing which dropped from 5.687MPa to 5.579MPa. A possible reason behind this result is that the flexural strength of the mortar reached its upper limit and from then on more or less maintained the same level of strength.

4.6 Porosity

The average porosities of specimens which were treated with different compaction methods at 7, 14, 21 and 28 days of curing are tabulated in the table below.

Table 6. Average porosity of specimens with different compaction methods at 7, 14, 21, and 28 days of curing

Compaction Method	Average 7 days Porosity	Average 14 days Porosity	Average 21 days Porosity	Average 28 days Porosity
Vibrate + VICM	28.47%	27.22%	24.04%	23.78%
Vibrate only	18.63%	18.59%	16.83%	16.02%
VICM only	31.09%	27.19%	24.34%	23.86%

Table 6 shows that the specimens compacted with the vibration compaction method had the lowest porosity compared to the other compaction methods which were vibration followed by VICM and VICM only. The porosity of the specimens which were compacted with the vibration compaction method showed a porosity of 16.02%, which was approximately 32.8% less than the others. Based on these results, vibration is efficient in reducing the porosity of the mortar. However, the same is not true if the mortar undergoes VICM after vibration compaction.

It is clear from the results that the porosity was highest in the specimens which underwent the vibration compaction followed by VICM. This reading was also close to that of the specimens treated with VICM only. The only valid explanation for this occurrence is that the pores in the specimen were open and interconnected. When undergoing the porosity test, these pores filled up with water, thereby resulting in a high reading for porosity.

For the specimens which underwent the vibration compaction only, there were a lot of closed pores inside the specimens which were not present previous to penetration by water. Hence, this led to a reading of low porosity.

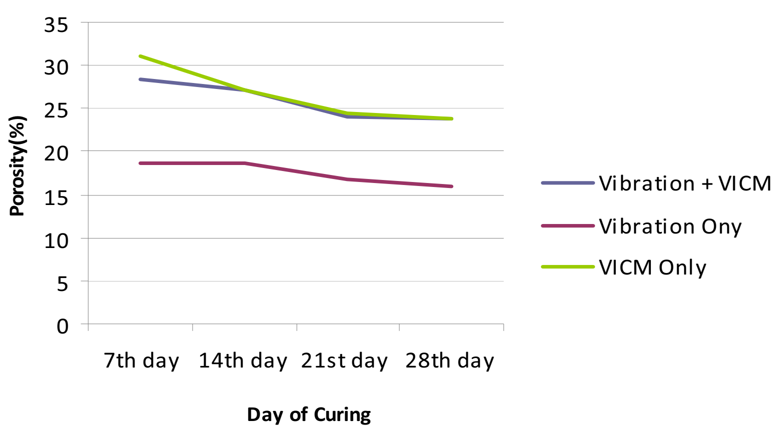

Figure 4 Development of porosity of specimens compacted with different compaction methods over the course of 4 weeks.

The graph in Figure 4 shows how the porosity of the specimens decreased as the curing age increased. As explained in earlier sections, the continuation of the cement hydration process refined the microstructure of the mortar and led to a reduction in porosity.

Table 7 Mean and Standard Deviation of porosity of all fabricated mortar specimens over the course of 4 weeks

Compaction Method	Mean (%)	Standard Deviation (%)
Vibration + VICM	23.78	1.516
Vibration only	16.02	0.278
VICM only	23.86	1.009

Based on Table 7 above, the standard deviation for the porosity of specimens compacted by the vibration method only was much less than the other specimens which were treated with the other two compaction methods. This occurred because the pores inside the mortar specimens compacted via vibration were closed pores which were relatively more impermeable to water penetration. This then led to a small deviation in the results for porosity. On the other hand, the specimens treated with both vibration followed by the VIC method and only the VIC method showed higher values in standard deviation. This might be because most of the pores in these specimens were open pores which were interconnected. Hence, it can be understood that the porosity of the specimens relies upon the degree of interconnectivity of the pores in the specimens. As more pores become interconnected in the mortar, the porosity of the specimen will increased.

5. Conclusion

This study was conducted via a thorough investigation on the mechanical development of mortar treated with different methods of compaction. Data was obtained and analysed from the first 4 weeks in the early stages of curing. Based on the results of the laboratory experiments, it can be concluded that the VICM can influence the microstructure of mortar and extract air bubbles trapped inside, thereby achieving the objective of compaction. It is efficient in extracting macro pores. As such, it is capable of attaining similar compressive and flexural strengths to those of mortar which is prepared by the conventional compaction method. However, the VICM is not efficient in extracting the micro pores inside mortar; it is only able to raise the micro air voids upwards, allowing them to concentrate in the region near the surface of the mortar. This type of high interconnectivity among the micro pores at the surface of the mortar contributes to high porosity. The air voids in the specimens which only underwent the vibration compaction method were closed air voids. The specimens that were compacted by vibration followed by VICM did not demonstrate better results in terms of compaction. Finally, it can be summarised that the porosity of mortar is inversely proportionate to the mechanical properties of the mortar.

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