Effect of Aggregate/Cement and Water/Cement Ratios on Concrete Workability

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Abstract
The characteristics of fresh concrete which defines workability are consistency, mobility and compactability. Several factors affect workability, but this study investigates the effect of Aggregate/Cement (AG/CM) and Water/Cement (W/C) ratios on workability of concrete. To achieve this, Slump, Compacting factor and modified vebe tests were carried out under ambient conditions of 26-30^{0}C temperature, 92% relative humidity and less wind on a fresh concrete;MC1, MC2, MC3, MC4, MC5 and MC6 of AG/CM and W/C ratios; 6.1, 5.0, 4.0, 3.0, 2.5, 2.1 and 0.6, 0.55, 0.5, 0.45, 0.4, 0.38 respectively. The investigation revealed that slump and compacting factor increases as the AG/CM and W/C ratios decreases suggesting that as workability increases the AG/CM and W/C ratios decreases. Results also showed that the Vebe time increases as the AG/CM and W/C ratios increases which means that it is less difficult to vibrate concretes of low AG/CM (≤3.0) and W/C (≤0.45) ratios. However, at W/C ratios of 0.45-0.4, the concrete remains very cohesive, consistent and workable (≥100mm slum, compacting factor 0.95) at AGG/CM ratios of 3.0-2.5. Again, the AG/CM increases as W/C ratio increases. Regression analysis carried out also showed that the regression coefficients (R^2) obtained from Slump-AG/CM, Slump-W/C, Compacting factor-AG/CM, Compacting factor-W/C, Vebe time-AG/CM, and Vebe time-W/C curves are 96.7%, 98.8%, 99.4%, 99.3%, 99.1%, 99.4% suggesting a clear relationship with each other in each case.

Key Words: *Workability, Slump, Compacting factor, Vebe time, Aggregate/Cement ratio, Water/Cement Ratio, Cement paste.*

1.0 Introduction

Fresh Concrete is said to be workable if it is easily transported, placed, compacted and finished without any segregation. Thus the characteristics of fresh concrete which defines workability are consistency, mobility, and compactability. Consistency is a measure of fluidity while mobility is the ability of fresh concrete to flow where it is placed. Compactability is the ease with which entrapped air, voids and segregation can be eliminated from a mix. Therefore, workability in practice offers an insight on plastic behavior of fresh concrete. This explains why a lot of research has been done on factors affecting workability. Such factors affect are aggregate size, shape and grading, porosity, admixture, ambient condition, AG/CM ratio, W/C ratio, time and temperature etc. Marar and Eren (2011), writes that as cement content increases, compacting factor increases but in relation with other constituents like water. Neville and Brooks (2002), also writes that for given cement, water and aggregate contents, the workability of concrete is influenced by the total surface area of the aggregate. The surface area is governed by the size, grading and shape of the aggregate. A well graded aggregate also helps in reducing voids making cement paste available for better lubrication (ACI 238.1, 2008). However, Kaplan, (2015) and Donzar et al, (2002) pointed out that angular and flaky aggregate reduces workability because they have greater surface area and more voids which reduces the available paste for lubrication. The porosity of an aggregate may also affect workability of concrete (Donzar et al, 2002, Cornelius, 1970, Hughes, 1960). If the aggregate can absorb more water, less will be available to provide the workability. The aggregate size influences the specific surface area, thus a finer aggregate will increase the required cement paste to effectively wet it, thus decreasing the workability while a coarser aggregate will increase the workability by providing a smaller surface area available for wetting (Duggal, 2012). Workability is also enhanced by the use of super plasticizers (ACI 238.1, 2008, Duggal, 2012). Workability is also defined as the amount of useful internal work or energy necessary to produce full compaction or overcome the internal friction between the individual particles of the concrete. This is evaluated by a Compacting factor test (Mehta and Monteiro, 1993). Consistency, which is the relative mobility or ability of freshly mixed concrete to flow (ACI Committee 116, 2000) is a measure of the wetness of the fresh concrete mix. It is evaluated in terms of slump, and it is the most widely used test for concrete at construction site (Ferraris and de Larrard, 1998; Neville, 2005). Okah and Okore (2016) concludes that un-agitated 1:3:6 concrete mix lost 75% workability which is far more than 43.8% for same agitated mix in 0-1hr time. That is to say that workability variation with time largely depends on the handling. Neville (2005) writes that temperature, humidity and wind velocity can affect the workability of fresh concrete. Corrnelius (1970) and Hughes (1971) had also stated that workability is relatively insensitive to cement content **alone** but in relation to other constituents hence, for practical reasons may be dependent on water content. The main aim of this research work is to investigate and establish the relationship between aggregate/cement and water/cement ratios and workability. Other factors like aggregate size, shape and grading, admixture, ambient condition, time and temperature have been researched upon on how they affect workability. However, of special interest to the researcher here is the effect of aggregate/cement (AG/CM) and water/cement (W/C) ratios which form significant criteria for a workable concrete.

2.00 Materials and Method

2.10 Materials

The cement used for this investigation in the laboratory was the Ordinary Portland Cement (OPC) of class 45.2R according to BS 4550. The fine aggregate was the locally available alluvial sand with specific gravity of 2.6 while the coarse aggregate was the locally available crushed rock sourced from Etche, Rivers State and Isiagu, Ebonyi State respectively all of Nigeria. The grading of the aggregate was according to BS 882 (1992). Drinkable water from tap was used for all the mixes. No chemical admixture or plasticizer was added. The experimental investigation was carried out under suitable ambient conditions of 26-30^{0}C temperature, 92% relative humidity and less windy condition.

2.11 Concrete Preparation

Table 1: Sieve analysis for fine aggregate

S/No	Sieve size (mm)	% passing
1	5.00	100
2	2.36	92.5
3	1.18	60.4
4	0.60	45.5
5	0.30	17.1
6	0.15	5

Table 2: Analysis for Coarse aggregate

S/No	Sieve size (mm)	% passing
1	30	100
2	15	90.2
3	10	21.4
4	5	5.0

The mixer was used as follows:

1) The required quantity of sand, coarse aggregate and cement were measured into the mixer.
2) Coarse aggregates, fine aggregates and cement were mixed for two minutes
3) The required quantity of water was added in thirty seconds and mixing continued for another two minutes
4) Mixing was stopped for one minute
5) Testing was delayed for 10 minutes

2.12 Mix proportions

Table 3: Various mix proportions

S/No	**Mix No**	**Mix Proportion (kg/m^3)**			
		Cement	**Sand**	**Coarse Aggregate**	**Water**
1	MC1	360	700	1500	216
2	MC2	410	650	1400	225
3	MC3	460	600	1250	231
4	MC4	520	540	1030	235
5	MC5	600	590	910	240
6	MC6	635	600	740	244

2.20 Test methods

2.21 Slump Test

Concrete slump test is to determine the workability or consistency of concrete mix. The slump test is the most simple workability test for concrete because it is inexpensive and provides immediate result. Therefore, it is widely used for workability test since 1922. The slump test is carried out as per procedures mentioned in ASTM C143 in the United States, BS 1881-102: (1993) and EN 12350-2 (2000) in Europe. The dimensions of the mould are: top and bottom diameters of 100mm and 200mm and a frustum height of 300mm. The slump test could be true slump, shear slump or collapse slump.

The mould is filled with fresh concrete in four layers each approximately; ¼ of the height (75mm up) and tamped with 25 strokes of tampering rod. The strokes are distributed in a uniform manner over the cross-section for the second and subsequent layers to penetrate into the underlying layers. The bottom layer is tamped throughout its depth. Thereafter, the concrete level is struck off using a trowel or tampering rod with the top of the mould completely filled. The mould is then removed by raising it slowly and carefully upward. This allows the concrete to subside and the slump measured by determining the difference between the original height of the mould and the concrete subsidence.

2.22 Compacting Factor Test

The test offers a direct and reasonable reliable assessment of workability of concrete according to BS 1881: Part 103 (1993). It is a measure of the degree of compaction imported to concrete. The concrete sample is placed gently in the upper hopper to its brim. Then the trap door at the bottom is opened for the concrete to fall into the lower hopper. After conical hopper has received the concrete, the cylinder is open and the trap door of the lower hopper is opened. The concrete is then allowed to fall into the cylinder with the excess concrete on top cut off. Then, the concrete in the cylinder is weighed as partially compacted concrete (W_1). The cylinder is then refilled with concrete from the same sample, in layers of 50mm. The layers is being heavily rammed or preferably vibrated to obtain full compaction and weighed as (W_2). Compacting factor is determined as the ratio of the weight of the partially compacted concrete to the weight of the fully compacted concrete (W_1/W_2).

2.221 Precaution: the test is sufficiently sensitive to enable differences in workability arising from the initial process in the hydration of the cement. Each test, therefore, is carried out at a constant time interval after the mixing, for comparable result is to be obtained.

2.30 Vebe Test

This test is sensitive to variations in workability of very dry mixes and precast concrete mixes. The test measures the time taken to transform or remold a standard frustum of concrete by vibration to a compacted mass according to BS 1881-104, EN 12350-3 (2000). Thus the time required to perform this action is the *vebe time* in seconds. A slump test was conducted first, and then a clear plastic disc was placed on top of the fresh concrete. The consistency is measured as the time taken to remold the concrete from the frustum shape to the cylindrical shape by sinusoidal vibration of the table.

3.4 Techniques

The aggregate/cement (AG/CM) and water/cement (W/C) ratios were obtained from the ***Table 1.0*** above and regression analyses conducted with the workability results obtained from the slump, compacting factor and vebe tests to establish a relationship between them.

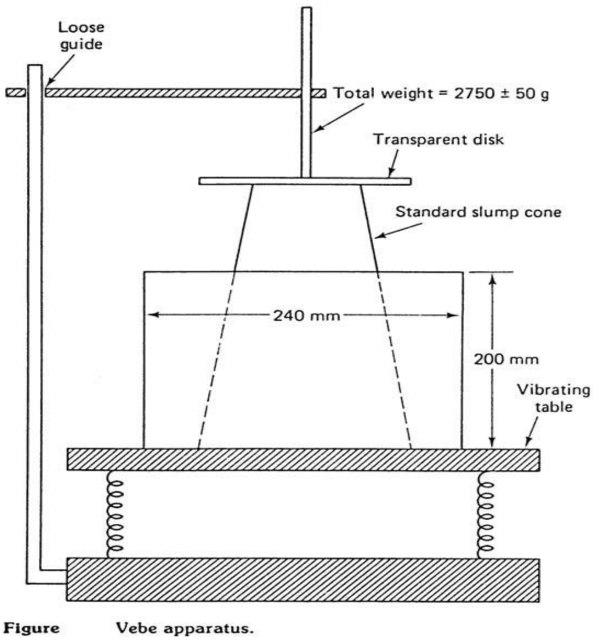

Fig 1.0: Vebe Consistometer Apparatus

3.0 Result and Discussion

Table 4.0: Result of study

S/No	Mix No	AG/CM Ratio	W/C Ratio	Slump (mm)	Compacting factor	Vebe time (sec)
1	MC1	6.1	0.60	80	0.91	5.5
2	MC2	5.0	0.55	85	0.92	5.0
3	MC3	4.0	0.50	90	0.93	4.2
4	MC4	3.0	0.45	95	0.94	3.5
5	MC5	2.5	0.40	100	0.95	3.0
6	MC6	2.1	0.38	105	0.96	2.8

3.10 Slump Test Result

3.11 Aggregate/Cement Ratio

As earlier stated according to Hughes (1971) that cement content alone cannot adequately explain the variation in workability, therefore, the interaction of the particles of the proportionate constituents of the concrete becomes very important in the determination of their relationship. From the result, slump increases as the AG/CM ratio decreases. This could be explained as follows: A decreasing AG/CM ratio means an increase in the available cement paste lubricating the surface area of the concrete in relation to the available aggregate. From the linear regression conducted in Fig 2.0, there exist a linear relationship between the AG/CM ratio and workability (Slump) with a correlation coefficient of 96.7%. The AG/CM ratio plays a crucial role in the inter-particle interaction or the binding ability of the cement on the available surface area of the aggregate which determines the workability. This relation is useful for this type of cement (OPC of class 45.2R) without any admixture in the field.

Interestingly, the quality of the concrete having slump, 95-100mm in Fig 2.0 is akin to that of reinforced concrete requiring little or no vibration for adequate setting and this is because, the available cement paste is adequate to bind the aggregates' surface area sufficiently facilitated by an appropriate W/C ratio.

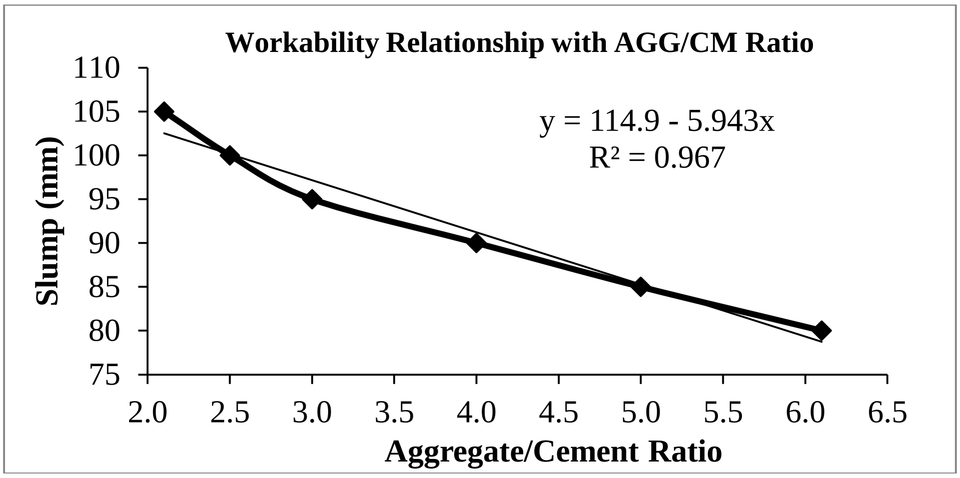

Fig 2.0: Effect of aggregate/cement ratio on workability (slump)

In this case, as the AG/CM ratio approach 2.1 and mix becomes richer, the workability becomes stable. From observation, once the slump exceeds 100-105mm; the mix shows signs of segregation indicative of a very wet concrete considered *collapse* concrete as the slump increases far more than 150mm and the AG/CM ratio is less than 2. For AG/CM ratio exceeding 4.0, the workability (slump) is relatively low (≤85mm) because the concrete is leaner due to poor cohesion and insufficient cement paste to bind the aggregates. Concrete of this quality is observed from the test to be harsh (Marar and Eren, 2011) and of same quality as mass concrete requiring massive vibration.

3.12 Water/Cement Ratio

Water/cement ratio defines the interaction between the water molecules and cement particles (cement paste) in facilitating proper binding. The quantity of water in relation to cement by weight as described in this study provides a profound knowledge on how this as a factor affects the quality visa viz the workability of the concrete.

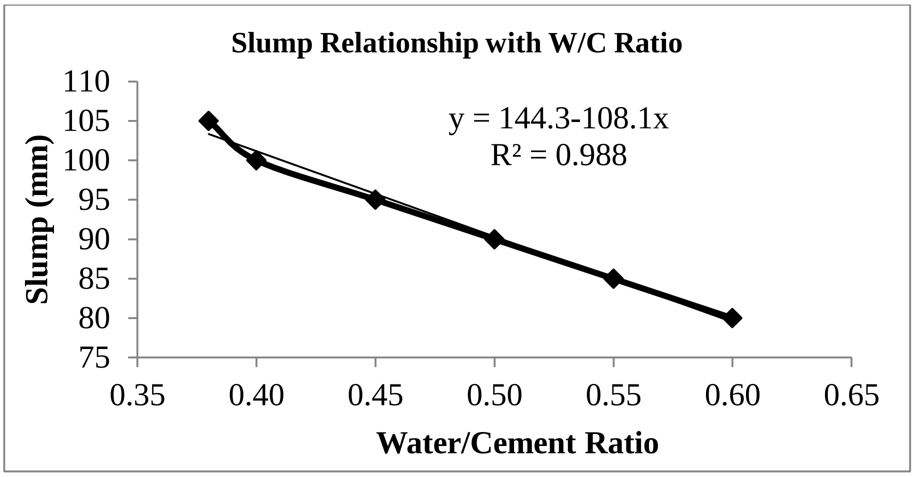

Fig 3.0: Effect of Water/Cement Ratio on workability (slump)

From the result above, slump increases as the water/cement ratio decreases and the linear relationship existing between them as shown in fig 3.0 has a correlation coefficient of 98.8%. At W/C ratio of 0.45-0.40 the concrete had slumps 95-100mm indicating a cohesive and consistent concrete very sensitive to slump and at these W/C ratios, the mix termed 'rich mix' is cohesive and the cement paste sufficiently bind the constituents facilitated by the interactive molecules of water which provides adequate medium for mobility and consistency. At W/C≥0.4 moving downwards, the concrete is becoming too insensitive to slump and the cement paste is insufficient to maintain cohesiveness and consistency. Further investigation shows that rich mixes requires less vibration in reinforced sections. On the other hand, W/C of 0.6-0.50 produced slump of 80-90mm with less cohesiveness and this type of concrete is termed harsh mix or lean concrete (Gani, 1997). However, keeping the W/C at 0.4 for AG/CM of 6.0-5.0 will definitely reduce the proportionate water quantity adequate to facilitate proper binding. Therefore, AG/CM and W/C are very crucial in determining the plastic behavior visa viz the workability of concrete.

3.20 Compacting factor

3.21 Aggregate/Cement Ratio

From observation of the result, the compacting factor increased progressively as the AG/CM decreased. The regression analysis carried out in Fig 4.0 shows that the logarithmic relationship between Compacting factor and AG/CM Ratio has a correlation coefficient of 99.4%. This relationship is valid and useful for this type of cement (OPC of class 45.2R) without any admixture in the field. As earlier stated, the compacting factor offers a measure of the amount of useful internal work necessary to produce full compaction by overcoming the internal friction between the individual particles in the concrete.

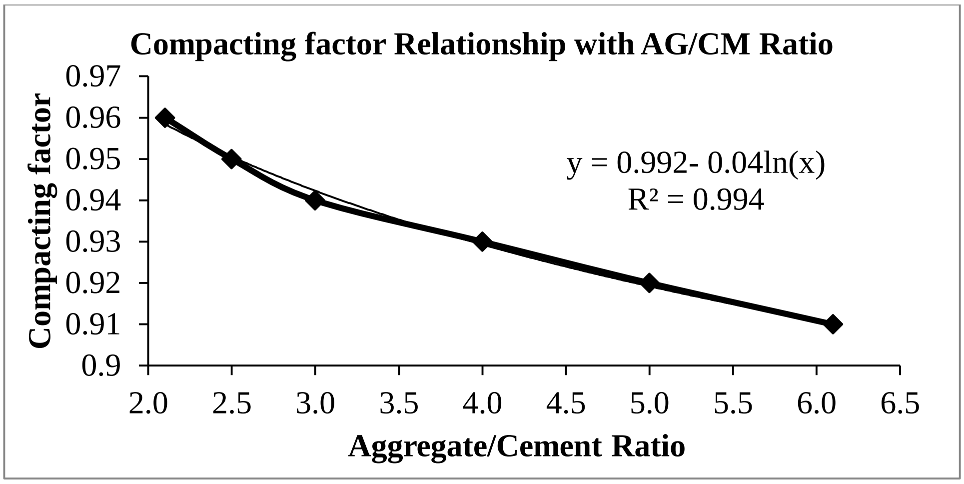

Fig 4.0: Effect of Aggregate/Cement Ratio on Compacting factor

Therefore, as the AG/CM decreases, the available cement paste increases hence, the concrete gains more internal energy to overcome the internal friction between the individual constituent particles thus allowing proper consistency. Fig 4.0 shows clearly the effect of aggregate/cement ratio on compacting factor (workability). For an AG/CM ratio of 3.0-2.1 compacting factor is high (0.94-0.96) because the cement paste is sufficient to overcome all forms of internal frictional resistance to mobility and consistency. At the increase of AG/CM ratio (4.0-6.1), there was a decrease in the compacting factor due to insufficient cement paste to lubricate the interacting surfaces and overcoming the internal friction of the constituent materials. Practically, for a given W/C ratio and aggregate shape (irregular/round smooth/rough), the AG/CM ratio is a determining factor of the workability hence, a decreasing AG/CM means an increase in the available cement paste lubricating the surface area of the concrete in relation to the available aggregate.

3.22 Water/Cement Ratio

From the result, the compacting factor increases as the water/cement ratio decreases. In this case, a decreasing water/cement ratio increases the cement content which provides sufficient cement paste and internal energy to perform internal work. This internal energy is to overcome the internal frictional resistances to do useful work of mobility. Fig 5.0 shows that the logarithmic relationship between Compacting factor and W/C Ratio has a correlation coefficient of 99.3%. This relationship is valid and useful for this type of cement (OPC of class 45.2R) without any admixture in the field.

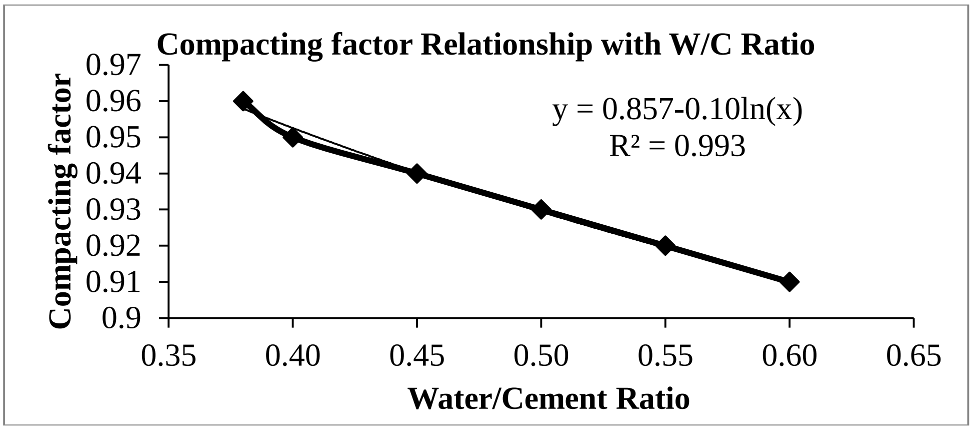

Fig 5.0: Effect of Water/Cement Ratio on Compacting factor

At W/C ratio of 0.45-0.4, the compacting factor is 0.94-0.95. This concrete as in Fig 5.0 is akin to that of reinforced concrete requiring little or no vibration for adequate setting. However, higher water/cement (0.50-0.60) ratios with higher AG/CM ratios (5.0-6.1) tend to produce concrete of less (reduced) consistency and workability similar to those used as mass concrete requiring massive vibration.

3.30 Vebe Time Result

3.31 Aggregate/Cement Ratio

Fig 6.0 shows that Vebe time increases as the aggregate/cement ratio increases. It is observed that as the AG/CM ratio decreases it becomes less difficult to transform the cone of concrete by vibration to a flat cylindrical mass. That is to say that less vibration hence less vebe time (sec) is required for complete vibration.

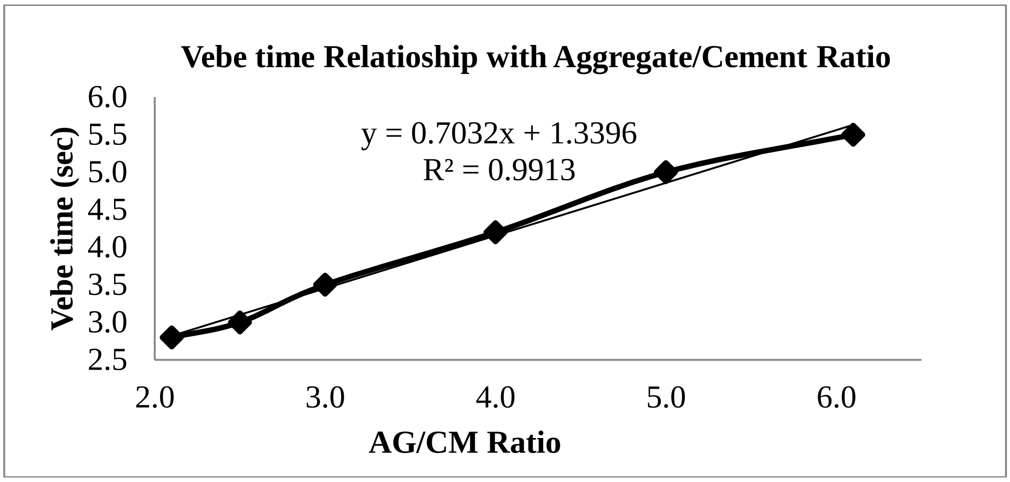

Fig 6.0: Effect of Aggregate/Cement Ratio on Vebe time

From Fig 6.0, at AG/CM ratio of 2.5 and 3.0, the vebe times are 3.0 and 3.5secs. Again, as the AG/CM ratio increases it becomes increasingly difficult to vibrate the compacted concrete hence more vebe time is required to flatten the compacted concrete. Fig 6.0 shows that at AG/CM ratio of 4.0, 5.0 and 6.1, the vebe times are 4.2, 5.0 and 5.5secs. The reason is attributable to the less available air spaces in the former case due to the availability of sufficient cement paste occupying the spaces and providing enhanced consistency and mobility while in the latter case, the porous condition (dry mix) of the concrete due to large air spaces made it increasingly difficult to disperse or vibrate the compacted concrete, hence longer vebe time is required. A linear regression conducted in Fig 6.0 showed that the regression coefficient is 99.1%. This relation is useful for OPC of class 45.2R without any admixture in the field.

3.32 Water/Cement Ratio

Fig 7.0 shows that Vebe time increases as the water/cement ratio increases. It is observed that as the W/C ratio increases it becomes more difficult to transform the cone of concrete by vibration to a flat compacted mass. In other words, a reduced W/C ratio makes it less difficult for complete vibration to a flat compacted mass due to availability of more cement paste to drive the workability; hence less vebe time is required.

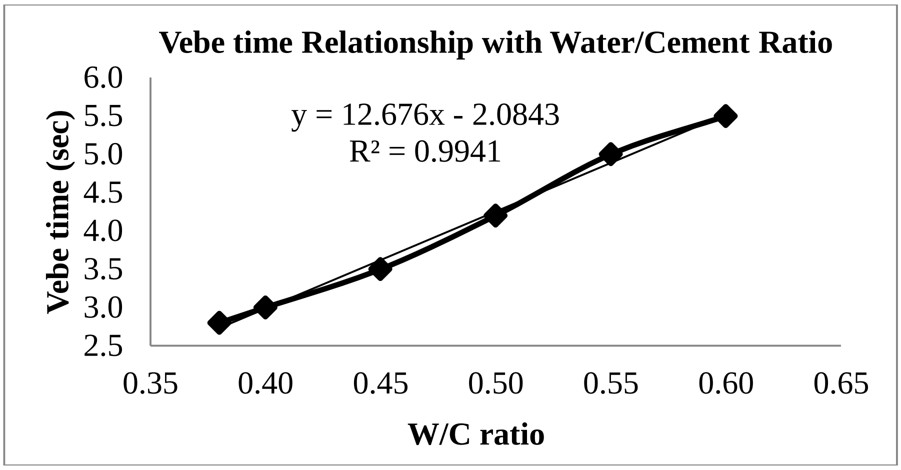

Fig 7.0: Effect of Water/Cement Ratio on Vebe time

A linear regression conducted to test the trend (Fig 7.0) shows that the regression coefficient is 99.4%. At W/C of 0.38-0.40, the corresponding vebe time is 3.0-2.8sec, but below this value, the vebe time is too small to be reliable.

3.40: Aggregate/Water Ratio Relationship with Water/cement Ratio

3.41 Aggregate/Cement Ratio relationship with Water/Cement Ratio

The AG/CM Ratio relationship with W/C ratio is shown below. The AGG/CM increases as W/C ratio increases. A linear regression conducted in this case showed that the regression coefficient is 98.8%.

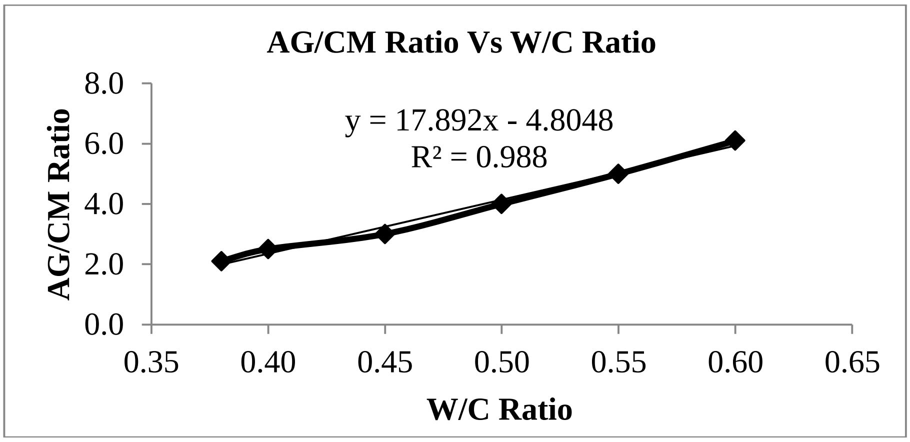

Fig 8.0: Relationship between Aggregate/cement and Water/Cement Ratios

Fig 8.0 shows that at the AG/CM ratios of 3.0, 2.5 and 2.1 the W/C ratios are 0.45, 0.4 and 0.38 respectively. From observation, an increased AG/CM ratio implies a reduction in the available cement paste in the concrete which also increased the W/C due to less available concrete paste. The slope of this curve is AG/W (aggregate-water ratio) which has little or no effect on workability.

5.0 Conclusions

From the result;

- Workability (Slump and Compacting factor) increases as the aggregate/cement ratio decreases
- Workability (Slump and Compacting factor) increases as water/cement ratio decreases
- The vebe time increases as the AG/CM and W/C ratios increases which means that it is less difficult to vibrate concretes of low AG/CM and W/C ratios
- The concrete also become richer and more workable as the AG/CM ratio approaches 2.1 from a higher value.
- Water/cement ratio is a very important factor in determining the behavior of plastic concrete because the fluid medium is provided by the water but in a proportionate quantity with cement to balance a point at which consistency and mobility is adequately maintained
- At W/C ratio 0.45-0.4 the concrete requires little or no vibration with workability (Slump ≥95mm, Compacting factor ≥94 and Vebe time ≤3.5 sec.) akin to a reinforced concrete section (with dense aggregates or prestressed). This, however, depends on the type and shape of aggregates used coupled with the AG/CM ratio
- Higher W/C ratios of (0.50-0.60) and AG/CM ratios of (5.0-6.1) tend to produce concrete of less (reduced) consistency and workability similar to those used as mass concrete requiring massive vibration
- The AG/CM ratio increases as the W/C ratio increases
- The slope of the AG/CM vs W/C ratios is AG/W ratio which has little or no significance in the on the workability of the concrete

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