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The Effect of Superplasticizer on Performance of Roller Compacted Concrete Pavement Containing High Volume Fly Ash

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Abstract: The use of roller compacted concrete pavement (RCCP) has increased noticeably over the last few decades, given its economic and environmental benefits. This type of concrete is known for its ability to incorporate natural wastes, such as fly ash. Moreover, to improve the performance and enhance the workability of RCCP, superplasticizer can be used. This study aims to investigate the effect of superplasticizer on the performance of high volume fly ash (HVFA) in RCCP. In achieving this aim, different mixtures of RCCP were prepared, where fly ash replaced 50% of the cement content, in addition to adding superplasticizer in quantities equal to 0%, 0.25%, 0.50%, and 0.75% by weight of the cementitious content. The results showed that up to 0.75% superplasticizer content that there was first, a positive relationship between the superplasticizer content and the compressive, splitting-tensile, and flexural strength. Secondly, increasing the superplasticizer content from 0% to 0.75% caused a noticeable improvement in the workability of the HVFA RCCP and caused a decrease in Vebe time of around 12 s. lastly, superplasticizer caused a reduction in porosity of HVFA RCCP and increased water absorption. Accordingly, this study revealed that it is possible to produce workable and durable concrete with high strength by adding superplasticizer to HVFA RCCP.

Keywords: Roller compacted concrete pavement, Performance, Superplasticizer, High volume fly ash.

I. INTRODUCTION

Roller compacted concrete is a special type of concrete that obtains its name from the unique procedure that is employed during its casting and placing, using heavy vibratory rollers [1]. During the last few decades, practitioners and researchers have recommended the application and use of RCCP due to its economic, operational, and environmental benefits [2]. From the operational and economic aspects, cement content is lower in RCCP than found in conventional concrete [3]. Also, RCCP does not need tie bars and steel reinforcement [4], and it is easy to be placed on-site [5].

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Further, RCCP requires fewer maintenance works and can sustain heavy loads in a quicker time, given it can develop early high compressive, flexural, and shear strengths [6]. Therefore, it is considered a suitable choice for emergency cases [7]. Furthermore, RCCP only requires low labour [8]. Similarly, the environmental advantage is also a result of the low cement content, which helps to decrease the need for producing and using this harmful material. Importantly, it also helps to reduce the problems that occur due to the heat causing hydration of cement, reduces the cement consumption, and CO^2 emission during production [3, 4]. RCCP can have a higher content of wastes and natural materials, such as fly ash, silica fume, and rice husk ash, which can replace the fine aggregates or the cement [9]. The use of fly ash, for instance, helps to improve the fresh and hardened properties of the concrete and reduce its cost [10]. Further, it helps to find a suitable place for the utilisation of fly ash, which is produced in vast quantities globally [9].

To achieve a high strength for the RCCP, the mixtures should be easier to compact using roller compaction [11]. The compaction of the RCCP is affected by the water to cement ratio, the aggregate gradation, and the shape and amount of the fine and coarse aggregates in the mixture [12]. The best compaction leads to a higher strength, and happens when the mixture is wet enough to avoid the sinking of the vibratory rollers [13]. However, RCCP is characterized as dry and stiff material, due to the low water and cement content [6]. To improve the consistency of the concrete with low water to cement ratio, water-reducing admixtures can be used [11].

Water-reducing admixtures are special products that can produce concrete of given workability and compaction at lower water to cement ratio compared to concrete without these mixtures [14]. Water reducing admixtures help to decrease the water demand, improve fluidity, enhance cohesiveness, reduce porosity, and consequently, contributing towards improving the strength, aiding compaction, enhancing durability, and achieving a better finish to the surface [6, 7, 15].

Superplasticizer is a high range water reducer, which is formulated from materials that help to achieve greater water reduction and higher workability compared to some of the other water-reducing admixtures. At the same time, it helps to avoid the side effects of other types, such as excessive air entrainment and set retardation [14].

The influence of superplasticizer can be explained by the cement dispersing mechanism that is created when superplasticizer is added,
which enhances the early hydration and improves the accessibility of water to the cement grain surfaces [16]? As a result, a higher early compressive strength is expected in the concrete with superplasticizer compared to one without superplasticizer [17].

Despite the higher need to increase the workability in the roller compacted concrete given its dry and stiff nature, it is rare to use water reducers, in general, or superplasticizer in this concrete [18]. In RCCP, water reducers must be added in high quantities, which increase the cost of the concrete [6]. In addition, the knowledge regarding the effectiveness of water-reducing admixtures in the RCCP is limited; their dosage should be determined in the labs, as they have an adverse effect if they are added in high quantities [19]. For these reasons, the use of water-reducing mixtures was substituted along with other methods and procedures. However, these methods lead to higher shrinkage in the mixture [6].

One of the methods used to decrease the cost of concrete and achieve better environmental and mechanical performance when using superplasticizer in the concrete is by using high volume fly ash superplasticized concrete. According to Mehta [15], this type of concrete might be one of the best "value-added" methods in using fly ash and superplasticizer in the concrete industry. The use of fly ash with a proportion up to 60% of the superplasticized concrete volume showed optimistic results in some earlier studies [20, 21]. Moreover, the concrete obtained satisfactory strength and durability properties got close drying shrinkage, creep, and freezing-thawing characteristics compared to those in conventional concrete. It also showed high resistance to water permeability and chloride-ion penetration.

In the RCCP, Rao and Kiran [22] investigated the impact of superplasticizer on the performance of RCCP. The experiment included three levels of superplasticizer; 0.5%, 0.75%, and 1% respectively. The results showed that among these three levels, the RCCP mixture that had 1% superplasticizer obtained the highest compressive, flexural, and tensile strengths. In addition, it was shown that the superplasticizer helped to obtain better workability in the RCCP.

Despite the benefits of the combination between fly ash and the superplasticizer in concrete, and the advantageous use of the RCCP, the number of studies investigating the effect of superplasticizer and fly ash on RCCP is limited. Further, the dosage of superplasticizer that should be used in the RCCP having high volume fly ash without creating an adverse effect remains an issue. Therefore, this study aims to study the performance of the superplasticized high volume fly ash roller compacted concrete pavement. This aim can be achieved by achieving the following objectives:

- Investigating the strength characteristics of the RCCP that has high volume fly ash and different dosages of superplasticizer.
- Investigating the workability of the RCCP that has high volume fly ash and different dosages of superplasticizer.
- Investigating the durability of the RCCP that has high volume fly ash and different dosages of superplasticizer.

II. RESEARCH METHODOLOGY

To achieve the objectives of this study, an experimental design approach was adopted by performing a group of field experiments to investigate the effect of changing the independent variables (superplasticizer content) on the dependent variables (performance).

2.1 Materials used

Cement: Ordinary Portland Cement OPC, confirming to Ms 522 part 1 was utilised. The OPC had a specific gravity and specific surface area equal to 3.14.
Aggregate: Fine aggregates (sand) and coarse aggregates of two sizes: 9.5 mm and 12.5 mm were employed in this study. The aggregate of size 9.5 mm with a specific gravity of 2.6%, and water absorption for 24 h of 1%. The aggregate of size 12.5 mm with a specific gravity equal to 2.62% and water absorption on 24 h of 0.45%.
Fly ash: The fly ash used in the RCCP mix design was fly ash (class F).
Admixtures: The admixtures used in the RCCP mix were Superplasticizer.
Water: Potable and drinking water.

2.2 Casting and mixing proportion

The materials used in the research were mixed based on the guide 211.3R-02 for selecting proportions for no-slump concrete [23]. Four mixtures were prepared, namely A1, A2, A3 and A4, as shown in Table 1. In all mixtures, 50% of the cement content was replaced with fly ash in order to produce HVFA RCCP. The first of the four mixtures was identified as the control mixture, where no superplasticizer was added. In the other mixtures, superplasticizer was added in three proportions of cementitious content; 0.25%, 0.5%, and 0.75% respectively. The proportion of aggregates and water content were the same for all mixtures. Table 1 displays the mix proportion details for all four mixtures.

Table. 1 Mix proportion details for the experiment's mixtures.

Mix No.	Cementitious materials	Cement	Fly Ash	Water	Coarse aggregates (Kg/m^3)		Fine aggregates (sand)	Coarse to fine aggregates ratio	Superplasticizer (% of cementitious content)
		Kg	Kg	(Kg/m^3)	9.5 mm	12.5 mm	(Kg/m^3)		
A1	12%	136.3	136.3	117.2	543.5	553	909.6	1:2	0 (control)
A2	12%	136.3	136.3	117.2	543.5	553	909.6	1:2	0.25%
A3	12%	136.3	136.3	117.2	543.5	553	909.6	1:2	0.50%
A4	12%	136.3	136.3	117.2	543.5	553	909.6	1:2	0.75%

2.3 Test methods

The performance of the mixtures was investigated using the following tests:

2.3.1 Mechanical properties

To investigate the compressive strength of the RCCP, the mixtures were cast in cylindrical specimens with 100 x 200 mm dimensions and tested on the 1st, 7th, and 28th days in accordance with ASTM C39 [24]. Similarly, for tensile strength, the mixtures were cast in cylindrical specimens with a 100 x 200 mm dimension and tested on the 1st, 7th, and 28th days in accordance with ASTM C496 [25]. Whereas, for flexural strength, the mixtures were cast in beams with dimensions of 100 x 100 x 500 mm and tested on the 1st, 7th, and 28th days in accordance with ASTM C78 [26].

2.3.2 Vebe time

Vebe time test is to assess the workability of the mixtures [27]. As RCCP is a zero-slump concrete, the workability is assessed using Vebe equipment. Vebe time is defined as "the vibration time required for a ring of mortar to form between the surcharge and the container wall" [28]. Vebe time test procedure is similar to a slump test for conventional concrete. RCCP with the necessary consistency to ease the compaction and form a uniform density would have a Vebe time between 10 and 45 s [30] and is conducted using Vebe equipment in accordance with ASTM C1170 [29]

2.3.3 Porosity

The Porosity test is one of the measures that predict the durability of concrete. The Porosity test was conducted on 5 cm samples that were cut from the 100 x 200 mm cylinder specimens. The samples were then dried in an oven at around 105 ± 5 °C for 24 h to remove any moisture before recording their weight. Next, each sample was placed in a vacuum desiccator where the vacuum valve was sealed, and the pump started. The pressure in the vacuum was decreased to 700 mm Hg, and the sample was left for approximately 3 h. After that, the water valve was opened, and water was allowed to cover the sample. During this process, the air was not allowed to enter. After that, the water flow was stopped, and the pump was kept running for one hour before the air was allowed to enter. The sample was then soaked in water for around 18 h to ensure that water filled all the pores in the sample. The sample was then removed carefully from the container, where its saturated surface dry weight was then measured [28]. The porosity was calculated based on the following Equation (2.1):

$$Porosity = 100\,x\,\frac{(Saturated\ surface\ dry\ weight - oven\ dry\ weight)}{(oven\ dry\ weight)} \tag{2.1}$$

2.3.4 Water absorption

The Water absorption test was conducted on 100 x 200 mm cylinder specimens. The specimens were first dried in an oven at around 105 ± 5 °C for 24 h and were then allowed to cool to room temperature where their weights were recorded before being immersed in clean water. After that, water absorption was measured based on two values. The first was for initial water absorption by weighing the specimens after 30 min, and the second measured the final water absorption by weighing the specimens following 72 h.

III. RESULTS AND DISCUSSION

3.1 Compressive strength

The compressive strength of concrete affects its quality and helps in determining the design needs [7]. According to Khayat and Libre [30], the compressive strength of the RCCP typically ranges between 28 MPa and 41 MPa. Also, based on ASTM C 1176 and ASTM C 1435, the cylindrical compressive strength of the RCCP should be higher than 24 MPa at the age of 28 days [6, 30, 31].

Figure 1 shows the values of compressive strength for the high volume fly ash RCCP. The Fig shows that on the day one, the compressive strength for mixture A1 (without superplasticizer) was the lowest compared to the other mixtures, and the highest strength was for mixture A4 having the highest content of superplasticizer among the four mixtures. The effect of the superplasticizer on the four mixtures is apparent from the first day, in contrast to the study of Atiş [17], in which the retarding effect of the superplasticizer caused a reduction in strength in the early ages of the superplasticized concrete in comparison to the concrete without superplasticizer. The compressive strength of the mixtures A2, A3, and A4 were increased by 7.1%, 21.4%, and 28.6% from that in mixture A1, respectively.

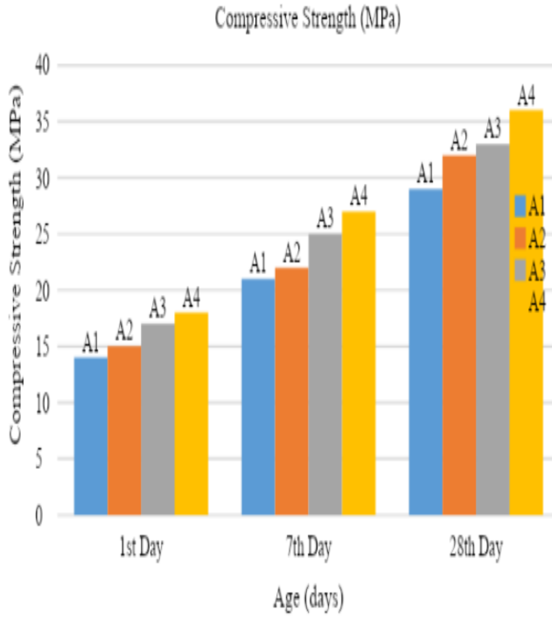

Fig. 1 Compressive Strength test

On day seven, the effect of the superplasticizer was also apparent, as the compressive strength in the three mixtures with superplasticizer were higher than that in the mixture without a superplasticizer. The more superplasticizer that was added to the mixture, the higher the compressive strength in the mixture. The compressive strength in mixture A2 was increased by 4.8% from that in mixture A1, while the compressive strength in A3 and A4 were increased by 19% and 28.6% from that in A1 respectively. Notably, the compressive strength in A3 and A4 on day seven was higher compared to what should be obtained on the normal RCCP on the 28th day according to ASTM C 1176 and ASTM C 1435. In addition, the compressive strength in A4 was very close to the typical compressive strength of the RCCP on the 28th day, according to Khayat and Libre [30]. In other words, RCCP with a high volume of fly ash and 0.75% superplasticizer content was able to obtain early high compressive strength comparable to the compressive strength in normal RCCP at later ages.

On the 28th day, similar results were obtained, for the mixtures with superplasticizer added, in increasing the compressive strength. The compressive strength was shown to be the highest in the concrete, with 0.75% superplasticizer (36 MPa). The increase in strength in mixtures A2, A3, and A4 was increased by 10.3%, 13.8%, and 24% from that in A1, respectively. In comparison to the other days, it appears that the gap between the values was the lowest on the 28th day. Also, it was observed that for the four mixtures, the concrete obtained a compressive strength associated with the typical ranges and above the minimum acceptable value of (24 MPa).

Therefore, in general, it can be said that adding superplasticizer caused an increase in the compressive strength for all ages used in the experiment.

3.2 Tensile strength

Tensile strength has a significant impact of the fraction mechanism of the concrete [33] and indicates the resistance to cracking. Indeed, tensile strength is used in the design of highways and concrete slabs [6, 30].

Typically, tensile strength ranges between 2MPa and 4MPa in RCCP [17, 34]. Figure 2 illustrates the tensile strengths for high volume fly ash RCCP. It was apparent from day one that the RCCP with high volume fly ash obtained high tensile strength given that from the first day, it was within the typical range. The highest tensile strength was found for mixture A4 (2.4 MPa), and the lowest was for mixture A1. The increase in tensile strength was also accompanied with the increase in the superplasticizer content as the tensile strength in mixtures A2, A3, and A4 increased by 10%, 17.5%, and 20% from that in mixture A1, respectively.

On day seven, a similar effect was observed for the superplasticizer regarding the compressive strength, which was observed on the tensile strength where adding superplasticizer caused an increase in the tensile strength. The increase in mixtures A2, A3, and A4 over the tensile strength in A1 was 7.7%, 15.4%, and 23% respectively.

Similarly, on the 28th day, the highest tensile strength was observed in mixture A4 (4 MPa, increased by 14.3% from that in A1), followed by A3 (3.7 MPa, increased by 5.7% from that in A1), and A2 (3.6 MPa, increased by 3% from that in A1). It was noticed that the tensile strength in the high volume fly ash with and without superplasticizer for all ages was within the typical ranges of the RCCP.

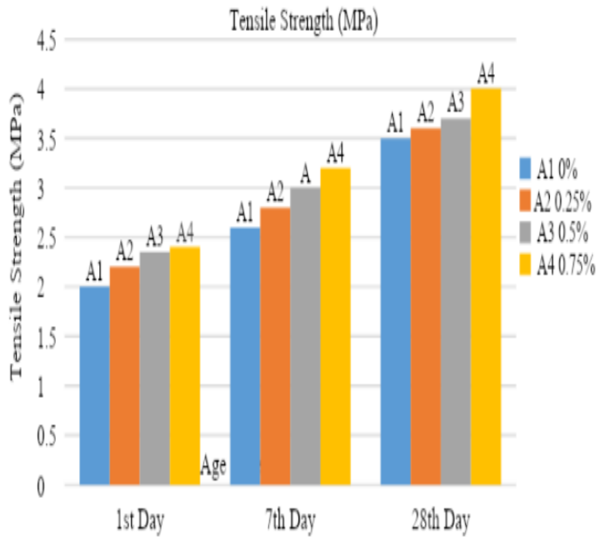

Fig. 2 Tensile strength test

According to Li [32], the ratio of tensile strength to compressive strength is typically around 10%. In RCCP, this ratio is usually between 5% and 15%, in which it decreases by the age of the RCCP [7]. Table 2 shows the ratio of tensile strength to compressive strength in all four mixtures. The table confirms the typical ranges, as the ratio ranged between 11.1% and 14.6%, decreasing over time for all mixtures. It also showed that this ratio was greater than 10%, which indicates that the high volume fly ash RCCP with and without superplasticizer obtained higher tensile strength in comparison to conventional strength.

Table. 2 Tensile strength/compressive strength ratio

Mixture	Super plasticizer content	1st Day	7th Day	28th Day
A1	0%	14.3%	12.4%	12%
A2	0.25%	14.6%	12.7%	11.3%
A3	0.50%	13.8%	12%	11.2%
A4	0.75%	13.3%	11.9%	11.1%

3.3 Flexural strength

Flexural strength in RCCP is usually higher than that in conventional concrete [31]. It is usually used in design requirement and in defining the ability to resist fatigue and thermal cracking [30].

The typical range for flexural strength in RCCP is between 3.5 MPa and 7 MPa. Figure 3 displays the flexural strength in all four mixtures of this study. As can be seen in the Fig, the flexural strength on day seven was the highest in mixture A4 (4.2) when the superplasticizer content was the greatest (0.75%). This value was 23.5% of that in mixture A1, where there was no superplasticizer followed by mixture A3 (0.50% superplasticizer), which was 14.7% of that in mixture A1 and mixture A2 (0.25% superplasticizer), which was 8.8% of that in mixture A1.

Similarly, adding superplasticizer had a positive effect on the flexural strength on the 28th day. Here, the flexural strength in mixtures A2, A3, and A4 increased by 16.2%, 21.6%, and 32.4% from that in A1, respectively. These values demonstrate that the impact of the superplasticizer on the flexural strength was more apparent over time, in contrast to the compressive and tensile strengths.

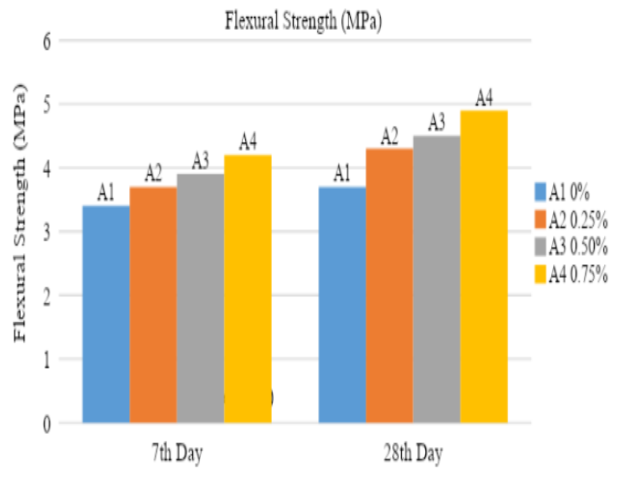

Fig. 3 Flexural Strength test

According to the British Airport authority [35], concrete can be used in airport pavement if it has a flexural strength above 4 MPa at the age of 28 days. As shown in Figure 3, it can be seen that mixtures A2, A3, and A4, having 50% fly ash and superplasticizer between 0.25% and 0.75% are suitable for this purpose.

In addition, the ratio of flexural strength to compressive strength is around 15% and between 10% and 12% in conventional concrete [30]. Table 3 displays the values of this ratio in all mixtures for all experiment ages. The table also shows that this ratio is between 12.7% and 16.8%, which indicates that the flexural strength in high volume fly ash, with and without superplasticizer is acceptable.

Table. 3 Flexural strength/compressive strength ratio

Mixture	Superplasticizer content	7th Day	28th Day
A1	0%	16.1%	12.7%
A2	0.25%	16.8%	13.4%
A3	0.50%	15.6%	13.6%
A4	0.75%	15.6%	13.6%

3.4 Vebe time

According to ACI 325, Vebe time in normal RCCP is usually between 30 and 40 s [28]. While Khayat and Libre [30] assert that in RCCP, in order to achieve better compaction, the Vebe time ranges between 10 and 45 s.

Figure 4 shows the value of Vebe time for all four mixtures in that all mixtures have an acceptable Vebe time, which helps to obtain the necessary consistency to achieve the needed compaction; as the Vebe time for the four mixtures is within the range between 10 and 45 s. In addition, it seems that by adding fly ash in high volume (50%) helped to achieve a lower Vebe time compared to that in normal RCCP.

Moreover, adding superplasticizer contributed to producing more workable concrete as the Vebe time decreases. However, the mixtures that have superplasticizer had Vebe time between 18 and 23 s. Therefore, adding superplasticizer caused a reduction in Vebe time by around 24% to 40%.

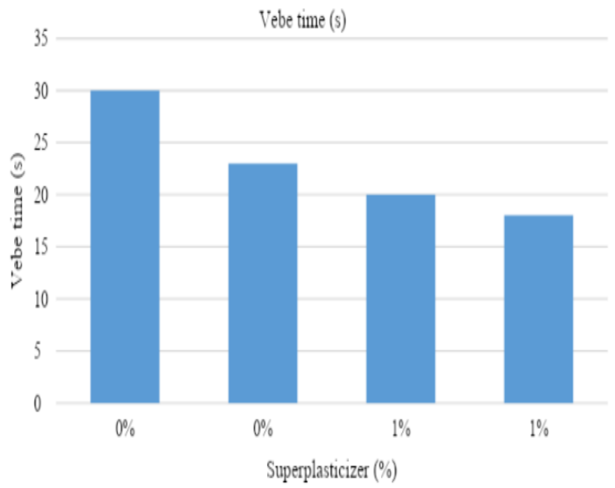

Fig. 4 Vebe time test

3.5 Porosity

Porosity measures the percentages of voids between the materials in the concrete according to the whole volume of its mixture, which ranges between 0% and 100%. It depends on the types and the sizes of the materials, the pore distributions, and compositions [36]. The lower porosity causes a more durable concrete, and excess porosity causes more penetration of water and air, leading to a reduction in the durability of the concrete [30].

Adding superplasticizer by 0.25% caused a decrease in porosity from 3.43 to 3.38 in comparison to the concrete without superplasticizer. The difference of porosity was around 0.13 in the concrete that had 0.50% superplasticizer and 0.18 in the concrete with 0.75% superplasticizer compared to that without superplasticizer. Where porosity usually affects the compressive strength, lower porosity, to some extent, is expected to produce higher compressive strength [30].

Figure 5 shows the relationship between the porosity and the compressive strength in this study. As shown in the Fig, the strong and negative relationship between the two parameters; the increase in the porosity is accompanied by a decrease in the compressive strength. The last point from the bottom right of the Fig depicts the case in mixture A1 (the control mixture), where the porosity was at its highest (3.43), and the compressive strength was at its lowest (29 MPa). Whereas, the point to the left of the latter is the case in which mixture A2 has 0.25% superplasticizer. At this point, the porosity decreased by 0.05% and the compressive strength increased by 10%. In mixture A3, the porosity decreased by 0.08% and the compressive strength increased by 3%. Finally, at the first point from the upper left of the Fig, which represents mixture A4 (with 0.75% superplasticizer), the porosity was at its lowest (3.25) and decreased by 0.05% from that in mixture A3 where the compressive strength was at its highest (36 MPa) and increased by 10% from the same mixture.

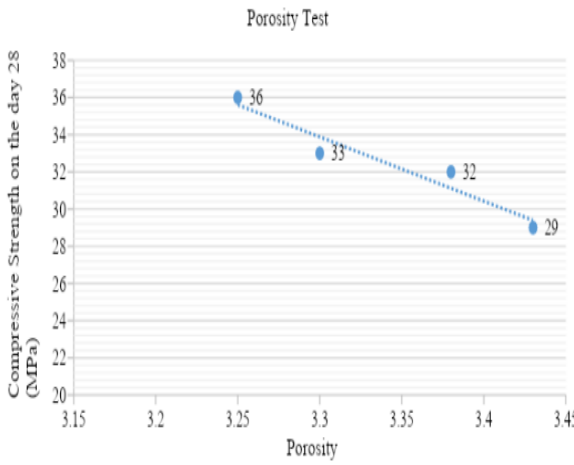

Fig. 5 The relationship between the porosity and the compressive strength

3.6 Water absorption

Figure 6 displays the percentages of water absorption for the mixtures in meeting the second objective of this study. As can be seen in the Fig, the initial and final water absorption in mixtures A1 and A2 were similar. However, when the superplasticizer content increased from 0.25% to 0.50%, the initial and final water absorption increased by 34% and 36% respectively. The initial water absorption in A4 was 3.06 times that as found in the control mixture, and the final was 2.27 times that in the control mixture. Therefore, it can be said that after the content of the superplasticizer increased beyond 0.25%, there was a positive relationship between the increase in the superplasticizer content and the increase in the initial and final water absorption.

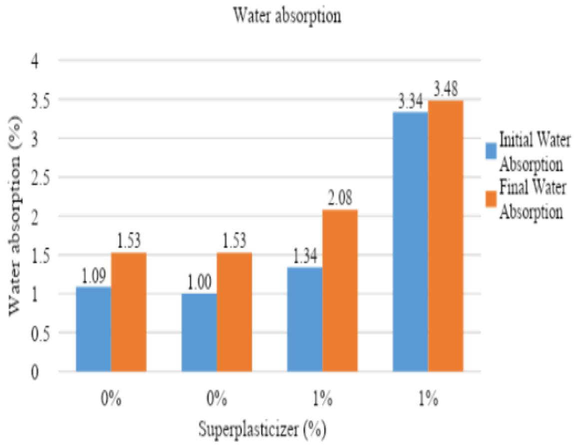

Fig. 6 Water absorption test

Therefore, based on the ranges identified by CEB-FIP [38] in assessing the performance of RCCP based on water absorption, it can be seen that only mixture A4 had average performance, while the other three mixtures had good performance based on water absorption.

IV. CONCLUSION

In this study, the effect of superplasticizer on the performance of HVFA RCCP was investigated through a series of experiments. The findings from the test results found that there is a positive relationship between the content of superplasticizer and the compressive, tensile, and flexural strengths. Also, for all ages of the mixtures, all mixtures with superplasticizer were able to obtain higher strength compared to the control mixture (A1). In comparison to the control mixture, on day 28, the compressive strength increased by 10.3%, 13.8%, and 24% in all mixtures that had 0.25%, 0.50%, and 0.75% superplasticizer content respectively. For tensile strength, these percentages were 3%, 5.7%, and 14.3% while for flexural strength, the increases were 16.2%, 21.6%, and 32.4%.

All mixtures in this study, including the control mixture, were able to obtain acceptable compressive, tensile, and flexural strengths. Increasing the content of superplasticizer in HVFA RCCP caused a decrease in Vebe time where the highest Vebe time was recorded in the control mixture (30 s), and the lowest was recorded in the mixture having the highest superplasticizer content (18 s). It was found that increasing the superplasticizer content in HVFA RCCP caused a decrease in porosity, which, in turn, affected the strength of the mixture. The highest porosity was shown in the control mixture (3.43), and the lowest was in the mixture with 0.75% superplasticizer content (3.25).

Moreover, the effect of superplasticizer on water absorption was shown to be insignificant when the content was less than 0.50%. However, when superplasticizer content was 0.50% or higher, there is a positive relationship between the superplasticizer content from one side and the initial and final water absorption from the other side.

Except for the mixture with 0.75% superplasticizer content, it was
observed that all mixtures had good performance based on water absorption.

Accordingly, the results of this study showed that by adding superplasticizer to the high volume fly ash RCCP, it is possible to produce a durable concrete having high strength and workability. However, the performance based on water absorption needs to be carefully considered in this case.

Several limitations were observed in this study. The first limitation was that the results of the tests were recorded in day 1, 7, and 28. Future studies should aim to investigate the performance at later ages of RCCP and HVFA RCCP (i.e. 90 days, 180 days or more). Secondly, this study investigated the effect of superplasticizer on the performance of HVFA RCCP by conducting laboratory tests. Future studies could validate the results of this study by conducting further fieldwork. Also, future studies could adopt an economic perspective in comparing the costs of these materials with the benefits. Lastly, future studies could employ higher contents of superplasticizer, or investigate other properties, such as freeze-thaw resistance.

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