Porosity and Water Absorption of Aerated Concrete with Varying Aluminium Powder Content

Rana Shabbar, Paul Nedwell, and Zhangjian Wu

***Abstract*—Pore space, which occupies 60 – 90% of the volume in aerated concrete, is important when considering performance. In this paper the properties of density, porosity, capillary suction and water absorption are investigated for aerated concrete produced. Aluminium powder was used with the percentage ranging between 0.25 and 1% by cement weight in order to produce the aerated concrete. Density, porosity and capillary suction tests were carried out after immersion in water for 28 days. The results show that the highest density of aerated concrete was with 0.25% aluminium powder. The porosity values obtained by vacuum saturation were consistently found to be higher than those obtained by soaking which suggests that the soaking method does not access all the pore space. Also, the capillary suction of aerated concrete as assessed by sorptivity was significantly higher than that measured by coefficient of water absorption method. However, both methods show the water absorption of aerated concrete increases with increasing aluminium content.**

***Index Terms*—Aerated concrete, density, porosity, water absorption and aluminium powder content.**

I. Introduction

Aerated concrete (AC) is a significant construction material. 60% to 90% of its volume is pore space. Pores are categorised as micro, macro-capillaries and artificial air voids with diameters between 100 nm and 4 mm [1], [2]. The properties of strength, durability, toughness, heat transfer and moisture transport are influenced by the pore size and microstructure [3]-[5]. A very porous material will produce excellent acoustic insulation and thermal properties. However, as the pore volume increases, the strength decreases. As a result, characterization of porosity and its effect on the mechanical strength of AC is an extremely important factor to be analysed when considering the manufacture of this kind of material [6]. The porosity and sorptivity of a concrete are affected by water content; for that reason a clearly defined condition must be used for testing [7]. Furthermore, incomplete drying results in retaining residual water in the pore system, particularly in the smaller pores.

Day and Marsh [8] used methods for assessing porosity by oven drying or re-saturation after oven drying which are equivalent methods. They studied the pore structure characteristics of cement paste containing fly ash. They concluded that the pozzolanic reaction of fly ash can lead to substantial reductions in porosity and that oven drying is the preferred process for assessing porosity. Struharova and Rousekova [9] studied the effect of the pore structure on density and compressive strength of cellular concrete. Their results showed that the pore structure is the main influence on these properties with the total pore size distribution ranging between 5 and 47 nm. The change in the values of porosity is small and there is no significant influence on compressive strength and absorbency of the cellular concrete. Kearsley and Wainwright [10] studied the porosity of foam concrete with the larger volume of cement replacement by classified and unclassified fly ash (up to 75%). It was noted that porosity is mainly dependent on the dry density of AC rather than the content or the type of fly ash. The volume of water absorbed by foamed concrete was twice that of the cement paste. The influence of Al (0.2% - 0.8%) on porosity, density and compressive strength of autoclaved clayey cellular concrete was studied by Gugliemi *et al*. [11] it was noted that the porosity increases by an increase in Al up to 0.4% and then decreases significantly between 0.6% - 0.8%. The mixtures with high Al content presented pores with a coalescence and non-uniform shape which were larger than those with low Al content. By contrast, density and compressive strength decreased slightly up to 0.4% and then increased as the porosity decreased. With a high amount of Al, part of the hydrogen gas was not effective in producing pores when the reaction between hydroxides and Al took place. Raj and John [12] studied the effect of different Al percentages (0.1, 0.2, 0.5, 1, 2 and 5%) on the bulk density and compressive strength of AC blocks. Their results showed that the dry density and compressive strength increased by increasing Al. Addition of more than 5% Al caused the compressive strength and density to decrease drastically. The aim of the current study is to investigate the effects of varying Al content on the density, porosity, capillary suction, and water absorption of AC after 28 days of water curing. Porosity and sorptivity samples with two different methods were compared.

II. Materials

A. Materials and Mix Design

Ordinary Portland Cement CEM I/52.5N with Leighton Buzzard Sand (0-2mm) were mixed in proportion 1:2. The water/cement ratio was 0.5. Daracem 215 superplasticizer (SP) and aluminium (Al) of purity 99.7% were added as shown in table 1. Warm water at 55 ℃ was added to accelerate the reaction throughout the experiment.

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B. Mortar Preparation

Sand and cement were put into a rotating drum mixer and mixed for 1 min; 70% of the water together with the SP were added and mixed for another 5 min. Then, Al was incorporated and mixed for an extra 30 seconds. Finally, the remaining water was added and mixed for 10 min. The specimens were demoulded approximately 24h after casting and then placed under water in a curing tank. For each combination of the parameters, two specimens were tested and the mean value is reported.

C. Test Specimens

Disks with a diameter of 75 mm and thickness 70±1 mm [13] were used to determine the density, porosity and sorptivity. The density of the AC was determined according to BSI 992 [14]. Porosity was measured according to BSI.1881-122 and by vacuum saturation as recommended by Hall [13], [15]. The capillary suction was measured according to BSI 772-11 and by the sorptivity according to Neville [16], [17].

TABLE I: MIX PROPORTION OF THE AC WITH DIFFERENT AL CONTENTS

Material	kg/m^3				
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Cement	350	350	350	350	350
Sand	700	700	700	700	700
Water	175	175	175	175	175
Aluminium powder	0	0.875	1.75	2.63	3.5
Superplasticizer (SP)	4.2	4.2	4.2	4.2	4.2

III. EXPERIMENTAL PROCEDURES

A. Density

1) Bulk density

Bulk density (P_{bulk}) is the ratio of mass (M_b) to the total volume of the sample including pores (V_b) [18], [19].

2) Solid density

Solid ("true") density is the density of material where there are no air spaces between the particles [19, 20]. The mass of the solid material without pores (M_s) and the volume of the material without pores (V_s).

B. Porosity

Pores are voids which filled with liquid or air. Between crystals in the solid material or gas bubbles in the hydration phase the cavities are formed [18]. Pores can be open and close and the porosity of AC was determined by two methods: water soaking and vacuum saturation.

1) Porosity by Soaking

The porosity measurement by soaking is termed "water absorption". The terminology used here is somewhat confusing. Porosity means the amount of water in the pore space, the term "water absorption" in this context suggests a capillary suction measurement. The porosities of the ACs were measured according to BS 1881-122 by drying the specimen at a controlled temperature of 105 ℃ ±5 ℃ for 72 ±2h. On removal from the oven, the specimen was cooled for 24± 0.5h and then weighed. The specimen was then immersed in a water tank to a depth of 25±5mm over the top for 30 ±0.5 min as shown in Figure 1. One specimen was then removed, shaken to remove excess water and surface-dried. The water absorption WA was calculated as the increase in mass caused by immersion expressed as a percentage of the mass of the dry specimen [21], [22].

Fig. 1. Porosity by water soaking.

2) Vacuum saturation porosity

Vacuum saturation is a method which is used to assess the total porosity of the material. Vacuum Saturation Apparatus was used to measure the porosity of AC after drying the specimens in an air oven at 100 ℃ ± 5 ℃ until the mass became stable [10]. The dried specimen was allowed to cool and then placed in a chamber which was connected to a vacuum pump. By pumping, the chamber was evacuated for 20 min. and then back-filled with water to cover the specimen. The sample was left to soak for a further 20 min as shown in Fig. 2 after the chamber was returned to atmospheric pressure [15]. The porosity was calculated from:

$$f = w_{sat} - w_{dry}/w_{sat} - w_A \qquad (1)$$

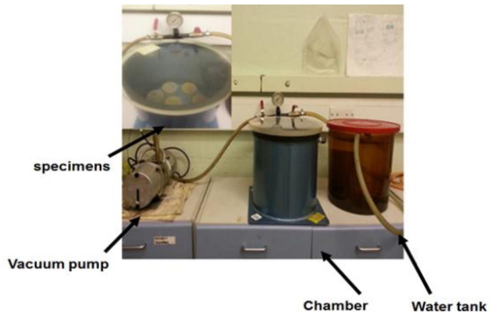


Fig. 2. Porosity by vacuum saturation.

C. Capillary Suction Tests

Capillary suction of AC was measured by sorptivity and coefficient of water absorption methods.

1) Sorptivity

A simple procedure to measure the sorptivity of mortar and bricks has been defined by Gummerson et al. and Hall and Tse [23], [24]. After drying the specimen to a constant mass at 70 ℃±5 ℃ in an air oven [17] it was placed, supported by a small plastic spacer, in a shallow tray containing water to a depth of about 5mm. The specimen was removed at regular intervals, surface-dried then weighed. Each weighting was completed within 30 sec. The water level was kept constant in the tray throughout. The weight of water absorbed was obtained at 1, 4, 9, 16, 25, 36, 49, 64, 81, 100 and 120 minutes then 24h and 72h, and the absorbed volume of water per unit area of absorbing surface was calculated for each, sorptivity (S) measured in mm/min1/2 and time in min. The cumulative water absorption *i* is proportional, during the initial absorption period, to the square root of the elapsed time t [25].

$$i = S\sqrt{t} \quad (2)$$

The sorptivity was calculated from the slope of the linear part of the i versus $\sqrt{t}$ curve. It is dependent on the initial water content and its homogeneity through the specimen under test. The point of origin in practice is neglected when the slope is determined on the graph. This is due to an increase in the mass of the specimen produced by filling of the open surface pores on the sides and inflow face of the specimen. To reduce these effects to a minimum it is essential to submerge the specimen in water between 2 and 5mm [16].

2) Coefficient of water absorption

The coefficient of water absorption was determined according to BS EN 772-11:2011. The specimens were dried in a ventilated oven at a temperature of 70 ℃ ± 5 ℃ until constant mass m dry was reached. They were then allowed to cool at room temperature at which point the dimensions of the faces to be immersed were measured and the gross area, As, calculated. As above the specimens were placed with their absorbing faces supported so that they were clear of the base of the tray and immersed in water to a depth of 5 mm ±1 mm for 10, 30 and 90 minutes [26]. The water level was maintained constant throughout the test and to avoid evaporation from the wet specimens, the tank was covered. After each immersion time (t so) the specimens were removed, the surfaces wiped and then weighed as mass of saturated surface (m_{sat}) and the coefficient of water absorption ($C_{w,s}$) calculated using the following formula. [17].

$$C_{w,s} = m_{sat} - m_{dry} / A_s\sqrt{t}_{so} \quad (3)$$

D. Absorption

A simple way to calculate the fluid penetration of concrete is determined by measuring the water absorption. The water absorption of the AC was measured by drying the specimen at a controlled temperature of 105 ℃ ± 5 ℃ until the mass became stable. On removal from the oven, the specimens were then submerged in a water tray to a depth of 3-5 mm for 7 days. The specimen was then removed, shaken to remove excess water and surface dried. The water absorption is calculated as the increase in mass caused by immersion expressed as a percentage of the mass of the dry specimen [21].

IV. Results and Discussion

A. Density

The bulk density of the AC specimens varied as a function of the Al percentage. It decreased significantly from 2101 kg/m^3 at 0% to 1489 kg/m^3 at 1% as shown in Figure 3. With increasing Al content, the bulk density of the AC systematically decreases due to a high amount of pores formed [11]. Similarly, Raj and John [12] pointed out an increase in Al causes a decrease in density with percentages of Al in the range 0.1% - 5%. It is interesting to note that the average solid density of the AC with the varying Al content was slightly higher 2216 kg/m^3 showing that even with no Al there were some pores present.

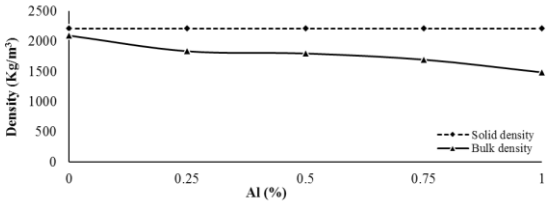


Fig 3. Bulk and solid density as a function of Al content.

B. Porosity

Porosity is the sum of the entrained air pores and voids within the paste. The porosity of the AC as measured by vacuum saturation was almost four times that measured by the water absorption method. By increasing the Al content, the porosity increased. The lowest porosity was obtained for the concrete with 0% Al which was 12% by vacuum saturation and 3% by water absorption as shown in Figure 4. The maximum porosity of the specimens tested was found to be 26% and 6% by vacuum saturated and water absorption respectively at 1% Al. However, Guglielmi *et al.* [11], observed that the porosity of an autoclaved clayey cellular concrete decreased when the Al percentage was increased from 0.6 to 0.8 %. They reported that pore coalescence is caused by the high reactivity of Al and at higher concentrations it is possible that the number of bubbles is so high it is more stable for them to coalesce into larger bubbles, which then escape, than to remain discrete. Ongoing microscopy will indicate whether this is the case. They also proposed that this problem could be reduced by minimizing the amount of superplasticizer in order to increase the viscosity of the cementitious paste so that the escape of the hydrogen bubbles would be reduced.

For this study, when the porosity of the specimens was measured by the vacuum saturation method, the specimen was completely dried until a constant mass was obtained. The vacuum withdraws all the remaining moisture from inside the pores. By contrast, the water soaking method indicated both incomplete drying (short period 72h) leading to residual water being left behind in the smaller pores in the pore system and also incomplete saturation since the water can only enter the material by capillary absorption at each face. Saturation is thus limited by the capillary transfer that can occur in 30 minutes.

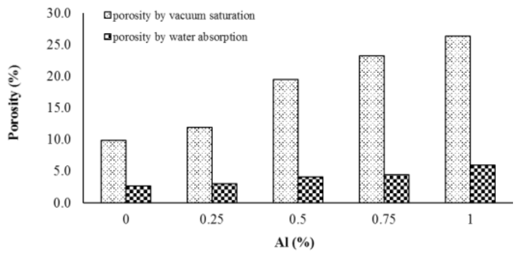


Fig. 4. Variation in porosity of AC with Al percentage.

C. Capillary Suction

Fig. 5 provides the plot of the cumulative water absorption against square root of time for AC specimens using the sorptivity method which shows two distinct phases. 1st phase described the water absorption for a short time period from 1 to 100 min. The trend of the line was straight and sorptivity is the slope of that line. This agrees with Sabir *et al.* [25] who tested the sorptivity of mortar containing ground bricks (10, 20 and 30% replacement for cement). How-ever, the trend of the 2nd phase, which describes the sorptivity of the AC specimens from 100 to 4356 min (72.6 h) was non-linear. A comparable trend was obtained by Hanzˇicˇ and Ilic [27] who also observed a non-linear trend for three different concrete mixes, concrete without additives, with an air entraining agent and with superplasticizer. They proposed this phenome non-refers to the new hydration of cement which took place when the specimen was placed in water and caused an increase of effective grain size which tended to block the micro-pores. Accordingly, water movement through concrete is hindered. Other trends of sorptivity were also obtained by Jennings and Tennis, where the cumulative water absorption against square root of time was a curve. Since there is a reduced amount of low density C-S-H gel, it is predictable that there is minimal swelling and shrinkage [28]. It can be seen that the mortar without Al content exhibits higher resistance to water absorption than those containing Al. In the current study, the sorptivity of AC increases with increasing Al content with the highest sorptivity being found at 1% Al. Fig. 6 (a) shows the cumulative water absorption against square root of time for AC specimens according to coefficient of water absorption method for the time range from 10 to 90 minutes. Fig. 6 (b) gives the values for sorptivity over a similar period. It can clearly be seen from the values for absorbtion that sorptivity is much higher than coefficient of water absorption. The relationship between sorptivity and Al percentage is shown in Fig. 7.

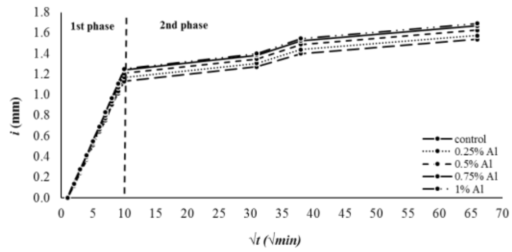
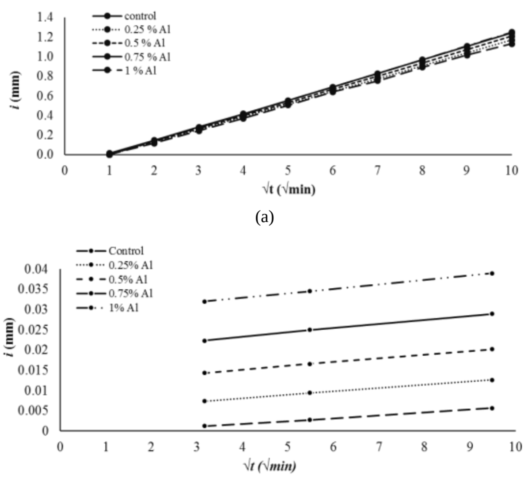


Fig 5. The cumulative water absorption against square root of time for AC specimens using the sorptivity method.



(a)

(b)

Fig 6. Cumulative water absorption per unit area of absorbing surface plotted against the square root of time for the AC containing various percentages of Al: (a) sorptivity and (b) coefficient of water absorption.

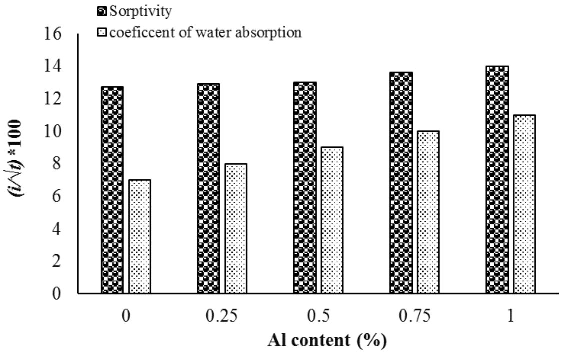


Fig 7. Dependence of sorptivity and coefficient of water absorption on different Al content.

D. *Water Absorption*

Water absorption of the AC mixtures is plotted against the density with the different Al content as shown in Figure 8. Water absorption is affected by the concrete mixture proportions, duration of curing and type, age or degree of hydration, existence of micro-cracks and the entrained air content [29]. Significantly, a higher percentage of water absorbed was in AC with lower density mixture. This may be due to the higher percentage of pores formed and capillary suction. For the AC specimens with high percentage of Al the water absorption at 3 days was greater than 7 days. It is suggested that initially the capillary pores are dry and the water absorption is high but then become more saturated with the time and cause less water absorption. It was noted that the lowest water absorption was 8.9% and 9.4% for the density 2102 kg/m3 and 0% Al content for 3 and 7 days respectively. However, the highest value was 11.1 and 10.7% for the density 1489 kg/m3 and 1% Al content for the same ages. The mixture with higher water absorption had higher density.

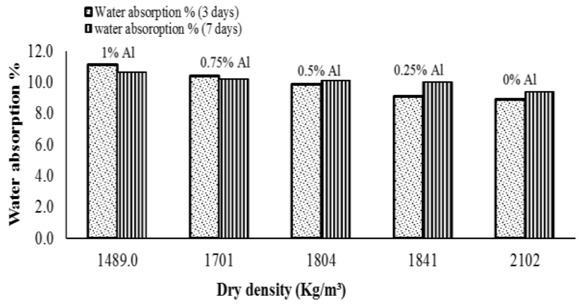


Fig. 8. Water absorption of AC against density with varying Al content.

V. CONCLUSION

This study aimed to investigate the influence of Al content on the density, porosity, sorptivity and water absorption of AC.

- By increasing the Al content, the bulk density decreased due to the large porosity formed. However, the solid density of AC with different Al content was almost the same.
- Porosity obtained by vacuum saturated method was more accurate than water soaking and it allows the total pore volume to be measured.
- Capillary suction assessed by sorptivity was significantly higher than the coefficient of water absorption method. The reason for this behaviour has yet to be explained.

• The water absorption of AC increased with decreasing the density for all the ages and the values were higher for the earlier age.

VI. Further Work

Methods for measuring sorptivity require further research

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