Capillary pressure measurement of crumb-rubber masonry concrete block

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ABSTRACT

This paper experimentally investigates the capillary pressure and porosity of masonry concrete block containing waste tyre (crumb-rubber) with varying ratios ranging from 0 - 25 %, which was used to partially replace coarse aggregate (granite) by volume. The bulk density of masonry concrete decreased by 5.4 % with crumb-rubber content up to 25 %. Porosity (*f*) of masonry concrete (24 hours water absorption, vacuum saturation, satiation, and vacuum satiation porosity) increased with an increase in crumb-rubber content. The capillary pressure test result for both the initial and refined (modified) method shows a rapid increase from 0 % to 5 % before gradually increasing with a further increase in crumb-rubber content up to 25 %. The average capillary pressure value for the reference masonry concrete using the initial and refined method is 0.166 MPa and 0.128 MPa while the modified concrete with 25 % crumb-rubber particles recorded 0.289 MPa and 0.233 MPa respectively indicating 74 % and 82 % increase respectively. Generally, the increase in capillary pressure can be directly linked to the increase in voids in the composite matrix which also increased the porosity. These results signify an increase in the capacity of modified masonry concrete to absorb water through the capillary rise.

Keywords: Crumb-Rubber; Masonry Concrete; Capillary Pressure and Porosity.

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ISSN No.: 2521-8263

CEMENT & CONCRETE SA

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This paper experimentally investigates the capillary pressure and porosity of masonry concrete block containing waste tyre (crumb-rubber) with varying ratios ranging from 0 - 25 %, which was used to partially replace coarse aggregate (granite) by volume. The bulk density of masonry concrete decreased by 5.4 % with crumb-rubber content up to 25 %. Porosity (*f*) of masonry concrete (24 hours water absorption, vacuum saturation, satiation, and vacuum satiation porosity) increased with an increase in crumb-rubber content. The capillary pressure test result for both the initial and refined (modified) method shows a rapid increase from 0 % to 5 % before gradually increasing with a further increase in crumb-rubber content up to 25 %. The average capillary pressure value for the reference masonry concrete using the initial and refined method is 0.166 MPa and 0.128 MPa while the modified concrete with 25 % crumb-rubber particles recorded 0.289 MPa and 0.233 MPa respectively indicating 74 % and 82 % increase respectively. Generally, the increase in capillary pressure can be directly linked to the increase in voids in the composite matrix which also increased the porosity. These results signify an increase in the capacity of modified masonry concrete to absorb water through the capillary rise.

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1. INTRODUCTION

Increasing amounts of solid waste materials are being investigated across the world to supplement natural components of typical building mixes, like concretes and mortars, due to environmental reasons. According to [8] each year about 9 million tonnes of waste rubber-tyres are disposed of all over the world, which was also estimated to be around 1 billion tyres withdrawn from use in the world annually. Based on 2018 statistics with a 15 % annual generation rate, it is estimated that around 37 million waste tyres exist in Nigeria [6]. In Nigeria one of the most common ways of disposing of waste tyres is through open field disposal, open-air combustion most especially in our abattoir and the local commercial quarry where they serve as a source of fire for processing slaughtered animals and mining activities [5]. Many researchers have studied and developed various recycling methods for the re-use of waste tyres in construction materials [9].

[1] has characterized crumb-rubber aggregate from end-of-life waste automobile tyres to have a low specific gravity (0.95 kg/m^3), small water absorption (2-4 %), low thermal conductivity (0.14W/mk) high dynamic modulus and damping properties and high resistance to weather (i.e non-biodegradable).

Masonry concrete in form of concrete blocks is becoming widely accepted as a construction material in our buildings, hence the partial replacement of mineral aggregates with rubber-tyre particles having low water absorption in concrete blocks would be a very good and promising way to utilize the large quantities of waste rubber-tyres. The use of waste rubber-tyres particles in masonry hollow concrete blocks would not only make good use of such waste materials by converting waste into a resource but could help to enhance some masonry hollow concrete blocks inherent properties such as water absorption. Masonry concrete blocks are porous material that interacts with the surrounding environment; their durability depends largely on the movement of water and gas as it flows through it.

Capillary pressure is the energy required to transfer a unit mass of liquid from a partially saturated porous material to a reservoir of the same liquid at the same temperature and elevation [2]. Porosity and saturated permeability do not tell the whole story of water transport in porous materials. Water movement in porous building materials is almost completely driven by the action of capillary forces. [3] described a new experimental method of measuring directly the capillary pressure of a wetting front. They showed that the capillary pressure is a material property and it defines the effective strength of the capillary forces that drive the absorption in a porous material. The method measures the equilibrium pressure of the air displaced and compressed ahead of the advancing wetting front. The pressure of air trapped in the wetted region is taken as the capillary pressure of absorption, using the assumptions of the ideal gas law.

The objective of this study is to investigate the bulk density, porosity, and capillary pressure of the reference masonry concrete compared to the modified crumb-rubber masonry concrete.

2. MATERIALS AND METHODOLOGY

2.1 Material

Crumb-rubber masonry concrete consists of cement, natural aggregate (fine and coarse), crumb-rubber from waste tyre, and water as shown in Figure 1. A general-purpose blended limestone portland cement CEM II (42.5R MPa) that conforms to BS EN 197-1:2011 with a specific gravity (G) of approximately 3.15 was sourced from a retail outlet and used for this study. Ordinary tap water (potable drinking water) sourced from Civil Engineering Laboratory was used for all concrete mixes and curing. Natural sharp river quartzite sand smaller than 4.76 mm but larger than 75μm that is free of clay, loam, dirt, and any organic or chemical matter with average specific gravity (saturated surface dry) of 2.65 and bulk density of 1,454 kg/m^3 was used as fine aggregate.

Figure 1: Crumb-Rubber Aggregate Used for Concrete Mix.

Natural crushed (granite) with nominal maximum sizes of 9.52-10mm and sourced from a local commercial quarry with a specific gravity of 2.66 and bulk density of 1,635 kg/m^3 was used as coarse aggregate. Coarse rubber aggregate (crumb-rubber) from scrap tyres with nominal maximum sizes of 4 - 9mm, the specific gravity of 1.14 and bulk density of 528 kg/m^3 was used for this research. Crumb-rubber surface treatment method by soaking in sodium hydroxide (NaOH) solution was adopted for this research due to its effectiveness in enhancing the hydrophilic properties of the rubber and increasing the intermolecular interaction forces between rubber and calcium silicate hydrate (C-S-H) gel which enhances the strength of the composite matrix as reported by [4]. Two-kilogram (2 kg) of Solid Caustic Soda (NaOH, Caustic Soda Pearls/Crystals ≥ 99.0 %) was dissolved in 10 liters of water to form liquid caustic soda also called saturated sodium hydroxide solution (NaOH) with a concentration of 10 % and pH of 14. Crumb-rubber particles were soaked in the saturated sodium hydroxide solution and stirred regularly to guaranty a uniform treatment of rubber particles for 24 hours under ambient conditions. The crumb-rubber particles were removed and washed with tap water and kept in laboratory condition for 24 h before use.

2.2 Mix Proportions

The mix design for the masonry concrete and crumb-rubber modified masonry concrete adopted was based on the absolute volume method according to BS EN 206:2013+A1:2016. Based on a preliminary estimate of the concrete mix design, a mix ratio of 1:1.5:3 with water/cement ratio of 0.42 and aggregate/cement ratio of 4.5:1 was used to produce a trial mix which was tested for compacting factor, strength, density and eventually subjected to adjustment before adopted and applied to all the concrete mixes. A total number of six (6) mixes were prepared: One control mix and five concrete mixes in which the 9.52-10 mm granite was replaced by crumb-rubber aggregate (4 - 9mm) at 5 %, 10 %, 15 %, 20 % and 25 % by volume. The mix proportions were constant in terms of mix design ratio, water/cement ratio, sizes, type of natural and crumb rubber-tyre aggregate used for the study.

Figure 2 : Masonry Concrete Samples for Water Absorption Coefficient Test.

2.3 Sample Preparation

The sets of hardened masonry concrete blocks prism samples used in this work with dimensions 160 x 40 x 40mm, were derived from masonry hollow concrete blocks using a masonry cutting machine as shown in Figure 2.

2.4 Experimental Procedures

(a) Bulk Density:

The bulk density of masonry concrete was determined from the eighteen (18) sample cured, oven-dried and heated until a constant weight was achieved. It was then cooled in a desiccator and weighed to the accuracy of 0.0018 after which they were transferred to a beaker and heated for 30 min to release the trapped air. They were cooled and the soaked weight (w) was measured. They were suspended in a beaker containing water placed on a balance. The suspended weight was taken and the bulk density was calculated from Equation 1.

$$\text{Bulk Density} = \frac{pw}{w-s} \bullet Kg \bullet m^{\cdot} \qquad \textit{Equation (1)}$$

Where: w = Soaked weight, s = Suspended weight,
and p = Density of water.

(b) Vacuum Saturation Porosity (f) Test:

Total accessible open porosity *(f)* was measured using this method as detailed in RILEM, CPC 11.3, and [7], although it is not a standard test method. In this method, the block was dried to constant mass at 70 °C ± 5 °C before being allowed to cool and weighed. The volume was determined. The eighteen (18) sample (average of three per test) was then placed in a vacuum chamber shown in Figure 3 which was connected by a hose to a rotary vacuum pump capable of producing a vacuum of ≈100 kPa. The chamber was evacuated and pumping was continued for 30 minutes. After which water was drawn into the vacuum chamber. When the sample had become fully immersed in the water drawn, the hose was removed from the water and air allowed to

Figure 3: Vacuum Saturation Porosity (f) Test.

$$f' = \frac{\text{volume of water absorbed}}{\text{volume of sample}} \times 100\% \qquad \text{Equation (2)}$$

enter the vacuum tank so that atmospheric pressure forces water into the evacuated pores of the blocks. After 24 h of soaking the sample was removed from the water and weighed.

(c) Water Absorption (24 Hours Soak) Porosity (Wm) Test:

The water absorption porosity test was determined according to BS EN 772-21:2011. The eighteen (18) masonry concrete samples were dried to constant mass and allowed to cool to ambient temperature before being weighed and the dry mass (m_d) was recorded. Then they were placed on small pads in a tank of water at room temperature to allow water to be in contact with all faces. The masonry concrete blocks were left submerged for the desired time (24 h in this study) then taken from the tank and surplus water is removed from their surfaces using a damp cloth. They were weighed and the wet mass (mw) was recorded. Wm was determined using Equation 3:

$$W_m = \frac{m_w - m_d}{m_d} \times 100 \qquad \text{Equation (3)}$$

Where: m_w = mass of the wet sample, md = mass of the dry sample. The percentage was calculated at soaking times of 1min, 9 min, 25 min, 1 h, and 24 h.

(d) Satiation Porosity (f') Test:

The satiation porosity also known as effective porosity was determined from one-dimensional capillary absorption using a simple procedure of measurement with only one weighing needed at the point when the water has reached the top face of the sample. Eighteen (18) blocks were dried at 70 °C to constant mass, allowed to cool to ambient temperature, their volume determined before they were weighed and the dry mass recorded. They were placed on their bed faces on small pads in a tank to an immersion depth of approximately 5 mm of water at room temperature to allow water to be absorbed from the bed face only until the water reached the top of the block. They were then taken from the tank, surplus water removed using a damp cloth, weighed and the wet mass was recorded and converted to volume. f' is equally calculated from Equation 4.

$$f' = \frac{\text{volume of water absorbed}}{\text{volume of sample}} \times 100\% \qquad \text{Equation (4)}$$

(e) Satiation Porosity (f") Under Vacuum Test:

In this method, the satiation porosity was determined in the same way as the vacuum saturation porosity. The difference is that water was fed into the bottom of a vacuum tank and stopped when the block bed-face had an immersion depth of approximately 5 mm. The eighteen (18) block samples remained under vacuum until the water reached the top of the block sample. Then the air was allowed to enter the vacuum tank and the block was removed from the water and weighed. The vacuum satiation porosity f" was then calculated from Equation 4.

(f) Capillary Pressure (ψ) Measurement of Crumb-Rubber Masonry Concrete:

Capillary pressure was measured using three rectangular prisms of dimensions 160*40*40 mm for every sample which was cut from each type of block with the long axis of the prism parallel to the bed and stretcher faces of the block. After drying the samples to constant mass in an air oven at 70˚C, five faces (the four long faces and one small face) were sealed with several layers of impermeable membrane. The initial masses of the bars were recorded and they were then fully immersed in water as shown in Figures 4.

The complete immersion of the samples enabled the detection of any air leaking through the sealed surfaces immediately by the appearance of bubbles. If bubbles appeared, the sample was recovered and recoated. The sealed sides ensured that absorption occurred only perpendicular to the inflow face.

Figure 4: Samples Sealed with Impermeable Membrane, Weighed and placed in Water.

The samples were weighed at regular intervals until there was no further change in mass. The volume of absorbed water was determined from the mass increase, giving the volume of pores filled with water. The capillary pressure was determined using Equation 6:

$p_1 v_1 = p_1 v_1$ {ideal gas equation assuming constant temperature} *Equation (5)*

Where: P_1 = the pressure of the initial volume of air in the block before capillary absorption and it is equal to the atmospheric pressure (0.1 MPa), V_1 = Initial volume of air (mm^3) = vacuum saturation porosity * sample volume, P_2 = Final pressure after absorption = trapped air pressure (MPa) and V_2 = Final volume of air left after the capillary rise of water (mm^3).

$$p_2 = \frac{p_1 v_1}{v_2} \qquad \textit{Equation (6)}$$

The capillary pressure (ψ) taken as P2 was calculated from equation 6.

3. RESULTS AND DISCUSSION

3.1 Bulk Density (ρ)

Bulk density for masonry concrete blocks determined is presented in Figure 5 which shows that the bulk density of masonry concrete decreased gradually with the increase in rubber content. The average bulk density of the reference masonry concrete is 2,577 Kg/m^3 while the crumb-rubber masonry concrete with 25 % crumb-rubber content recorded a bulk density of 2,439 Kg/m^3 respectively which indicates a 5.4 % decrease in density with 25 % replacement of crumb-rubber.

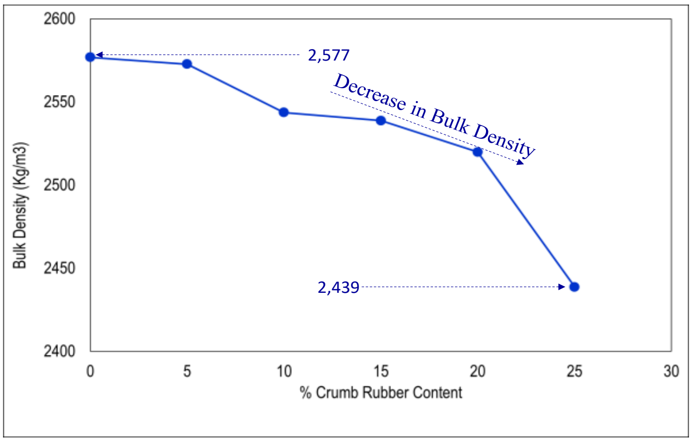

Figure 5: Bulk Density (Kg/m^3) of CR-MCB Against % CR Content.

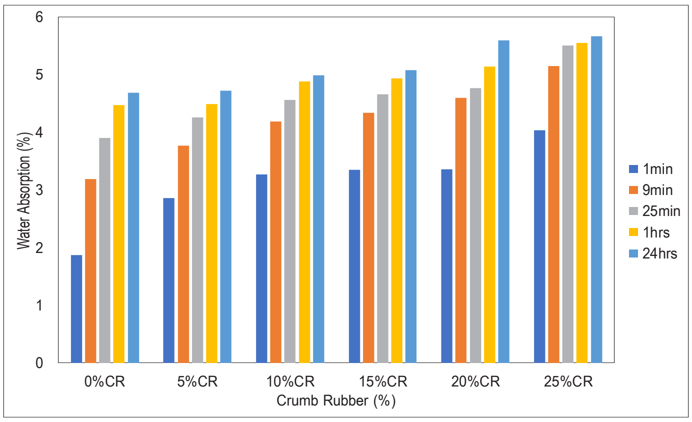

Figure 6: Water Absorption Porosity Test of CR-MCB Against % CR Content.

3.2 Water Absorption (24Hours Soak) Porosity (*f*)

The 24 hours water absorption porosity test of masonry concrete is presented in Figure 6. The results indicate that increase in crumb-rubber content increased the porosity of masonry concrete samples by 21 % with 25 % crumb-rubber replaced in coarse granite aggregate.

3.3 Vacuum Saturation Porosity (*f*)

The porosity of masonry concrete using vacuum saturation test is presented in Figure 7. The result of the vacuum saturation porosity measurements provides a true porosity, i.e., per cent by volume, unlike the 24 hours soaking porosity test which many others do refer to as a substitute for porosity but not a porosity. The results show that the reference masonry concrete samples (0 %CR) have a porosity of 23.69 % while the 5, 10, 15, 20 and 25 % have a porosity of 23.75, 23.94, 24.03, 24.12 and 24.38 % respectively.

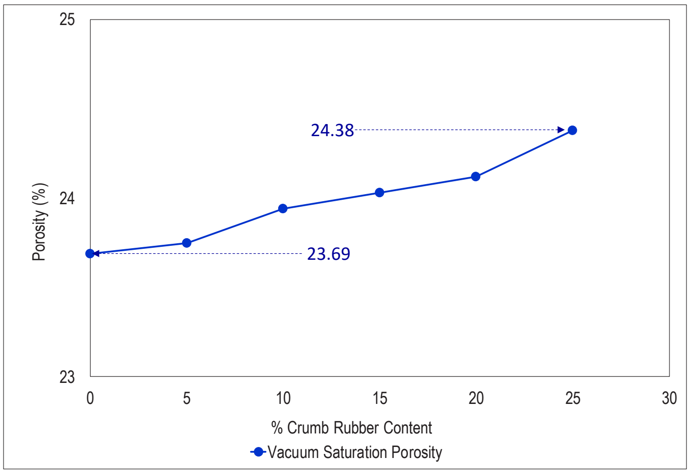

Figure 7: Vacuum Saturation Porosity (f) of CR-MCB Against % CR Content.

3.4 Satiation Porosity (*f'*)

The results of satiation porosity also known as effective porosity of crumb-rubber masonry concrete blocks are presented in Figure 8. The results show that the reference masonry concrete blocks (0 %CR) have a porosity of 13.62 % while the 5, 10, 15, 20 and 25 % have a porosity of 13.78, 13.99, 14.10, 14.52 and 14.71 % respectively.

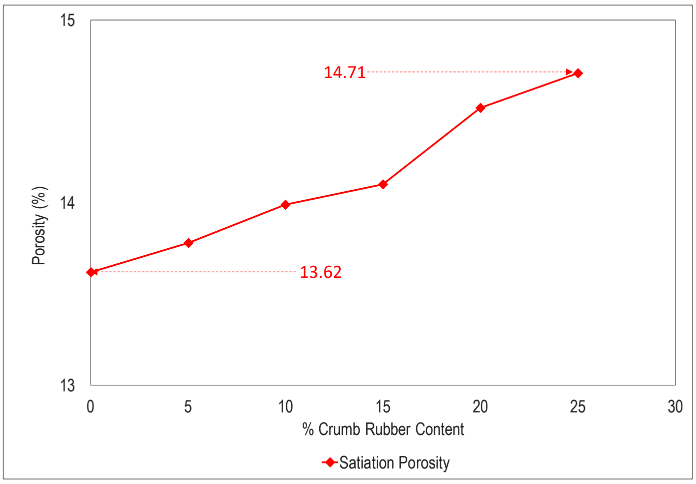

Figure 8: Satiation Porosity (f') of CR-MCB against % CR Content.

3.5 Vacuum Satiation Porosity (f'')

The result of the vacuum satiation porosity measurements provides values very close to the vacuum saturation porosity (*f*) as shown in Figure 9. The results show that the reference masonry concrete (0 %CR) has a porosity of 23.63 % while the 25 %CR have a porosity of 24.36 % which indicate an increase with about 3.1 %.'

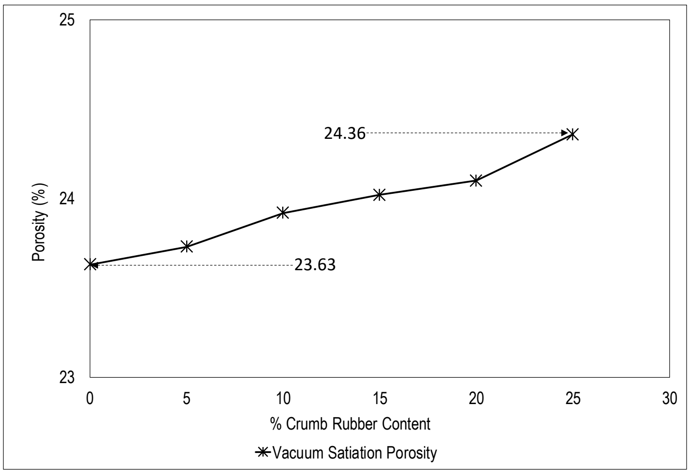

Figure 9: Vacuum Satiation Porosity (f'') of CR-MCB Against % CR Content.

3.6 Capillary Pressure (ψ)

The capillary pressure test result for both initial and refined (modified) methods is presented in Figure 10 which shows that the capillary pressure of crumb-rubber masonry concrete increased rapidly from 0 % to 5 % crumb-rubber content before gradually increasing with further increase in crumb-rubber content up to 25 %.

The average capillary pressure value for the reference masonry concrete using the initial method is 0.166 MPa while the masonry concrete with 25 % crumb-rubber content recorded capillary pressure of 0.289 MPa which indicates a 74 % increase in capillary pressure with 25 % replacement of crumb-rubber. For the refined (modified) method, average capillary pressure of 0.128 MPa was recorded for the reference masonry concrete while the masonry concrete with 25 % crumb-rubber content recorded capillary pressure of 0.233 MPa which indicates 82 %.

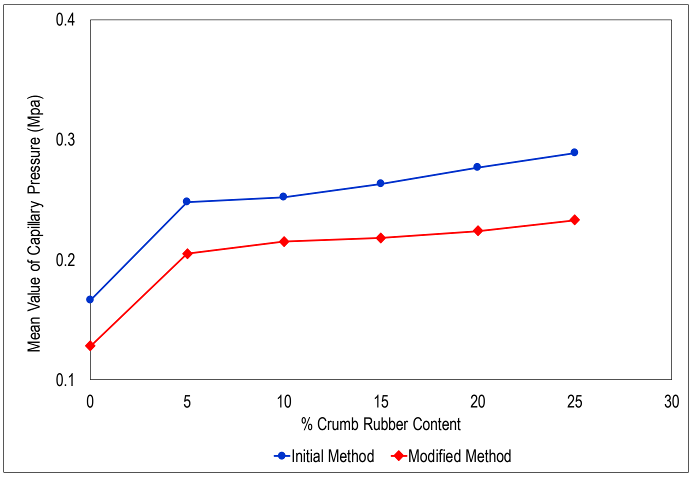

Figure 10: Capillary Pressure (ψ) of CR-MCB Against % CR Content.

4. CONCLUSIONS

i. The bulk density of masonry concrete decreased with a percentage increase in crumb-rubber content up to 25 %. The reference masonry concrete recorded 2,578 Kg/m^3 while 25 % crumb-rubber modified masonry concrete has a bulk density of 2,439 Kg/m^3 which indicates a decrease of 5.37 %.

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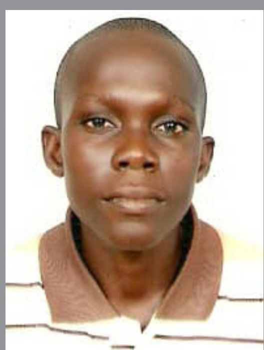

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ii. Porosity (*f*) of masonry concrete samples (24 hours water absorption, vacuum saturation, satiation, and vacuum satiation porosity) increased with an increase in crumb-rubber content varying from 5, 10, 15, 20 and 25 %. The increase in the porosity is related to the higher content of entrained air along with poor interfacial contact between the crumb-rubber particles and the cement paste, the masonry concrete mixes caused by the hydrophilic (non-polar) nature of crumb-rubber particles attracting air around the surface of the aggregate during the mixing process causes a weaker bond between the non-polar and the polar particles, pores in crumb-rubber particles and the complex morphology of crumb-rubber.
iii. Capillary pressure (ψ) of masonry concrete increased rapidly from 0.166 MPa to 0.248 MPa for 0 % and 5 % crumb-rubber content before gradually increasing up to 0.289 MPa for crumb-rubber content up to 25 %. Generally, the increase in capillary pressure for both the initial and refined method with an increase in crumb-rubber content can be directly linked to the increase in the volume of pore spaces (voids) as a result of weak bonding between the crumb-rubber and the concrete composite which increased the porosity and results to increase in the volume of capillary rise.
iv. The result signifies an increase in the capacity of the modified masonry concrete to absorb water through the capillary rise **CB**

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