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The Influence of Pores Size and Type of Aggregate on Liquid Mass Transfer in Porous Media

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Abstract: This research aims to investigate the capillary transport properties of concretes and natural stones as to be used as an absorber plate material of solar distillation equipment. Macro scale photograph and porosity test has been doneto determine the characteristics ofthe porous medias. In order to analyze the transport properties, a sorptivity test was done in this study. Two different types of concrete was filled with Lumajang's sands and ferrous sands as the fine aggregates. Both types of concrete were then divided with two different particle size which were 0.125 and 0.250 mm in diameter, respectively. A natural stone was used as a comparison materials. The results taken from macro scale photographs showed that increasingsize of pore holes with the larger aggregates particle's size in both types of aggregates. The highest porosity was found in concrete with ferrous sand with aggregate size of 0.250 mm specimen with a value of of 57.77%. The highest porosity was gained in concrete with Lumajang sand with aggregate size of 0.250 mm specimen with the amount of 0.224%. The largest volume of absorbed seawater and sorptivity coefficient was also obtained in concrete with Lumajang sand with aggregate size of 0.250 with the value of 8.05 mL and 9.58×10^{-5} m/sec$^{0.5}$, respectively. However, concrete with ferrous sand with aggregate size of 0.250 has the highest mass flow rate with the value of 3.25×10^{-7} kg/sec. The interconnectivity between the channels also has a significant role in mass flow rate value which occurred in natural stone specimen.

Key words: Porous media, mass transfer, capillary flow, aggregate, natural stone, characteristics

INTRODUCTION

Porous media is a solid-type material which has interconnected voids or empty channel in it. In dry condition those empty spaces are filled with the air while in a wetted condition the air replaced by liquids.Within a wetted porous media, the liquids could shaped a thin film formation. Which in this form, the liquids has a larger contact area with the material. In a heat transfer point of view, along with larger contact area will leads into a faster heat transfer rate. These condition causes the efficiency of a heat transfer apparatus becomes higher. One of the application which using porous media as a heat and mass transfer medium is the absorber plate on solar still. Pankaj and Agrawa (2013) added some floating porous material in order to obtain a higher evaporation. Ranjithkumar *et al*. (2015) used porous media such as gravel, sponge and etc. as an addition material above the absorber plate. While in this study, the concrete and natural stone material are proposed to be used as an absorber plate.

The stone and concrete is a type of porous media that can be easily obtained and processed. Beside that, the stone and concrete materials does not corrode like the metallic based porous media. Stone and concrete material are suitable to be applied as an absorber plate in solar still. This application has a high corrosion risk due to the salt water that takes place as the working fluids. Moreover, the research of stone and concrete material as a heat and mass transfer in a finned absorber plate model has not been performed yet. This research focused on mass transfer phenomenon occurred in porous media, especially on the stone and concrete materials. Beyhagi *et al*. (2014) declared that some parameters such as porosity, the number of holes and the pore diameter of a porous media has a significant role to its mass transfer phenomena. Meanwhile, some aspects that affectsthose parameters in a concrete material is the type and particle size of the sand which used as it's aggregate.

Mass transfer in porous media mainly caused by three type of phenomena such as diffusion, suction and capillarity. The driving force in diffusion phenomena is the difference in concentration. While in suction phenomena is the fluids movement mainly due to pressure difference. And capillary action have the fluid's surface tension as its driving force (Hanzic and Ilic, 2003).

Diffusion is the main mechanism of mass transfer that occurs when the concentration difference between the

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two phases is high enough. Suction phenomenon occurs on a systems with high pressure difference and generally only happen on a large pore area. The effect of surface tension whichisfairly small can be negligibleif compared with the higher value of the pressure difference. On the other hand, capillarity occurs in a smaller pore holes, where the force of the fluid tohigherelevationdue to its surface tension. This type of fluidsmovement only occurs when the capillary force are greater than the fluids weight force (Hanzic and Ilic, 2003).

In a finned absorber plate withporous media material, the mass transfer that occurs are dominated by capillarity phenomenon. In this application, the sea water as the working fluid streams upward against gravity along the channel or cavities inside the porous media. Such conditions occur naturally without any coercion or extra energy from outside the system to create the working fluid movements. Some parameters such as surface tension, contact angle and viscosity of the fluid which works against the porous media plays an important role on the rate of fluid movement. When the attractive forces among fluid's particles is smaller than the attractive forces between the fluid's particles and porous media can make the fluid particles moves upwards against the gravity (Cengel and Cimbala, 2006). In other words the presence of capillary movements, only occurs when the cohesion from fluid's particles are smaller than it's adhesion. The effect of larger porosity leads to a higher seepage velocity in downward porous media flow. Thus in this research the flow occurred in upwards direction and the effect of porosity needs to be further investigated.

Therefore, the gravimetric analysis needed to clarify the overall amount of fluid into the porous media (Hanzic and Ilic, 2003). Sorptivity [m $sec^{-1/2}$] is another coefficient parameter which determine capillary movement based on volume of absorbed liquid. Hence, the relationship between time and the absorbed liquid's volume represented in these following equation (Hanzic and Ilic, 2003):

$$i = s\sqrt{t} \quad (1)$$

Where:

i = The absorbed fluid's volume per unit area (m)
s = Sorptivity coefficient (m $sec^{-1/2}$)
t = Time (sec)

This research aim toa further investigation on the characteristics of mass transfer in porous media, especially in stone and concrete materials. Some parameters such as granular size and types of fine aggregate in concrete materials effect towards the surface characteristic, porosity and mass flow rate were studied. The natural stone were also studied as a comparison between natural and artificial porous media. In the end, this study would determine the most suitable type of porous media to be used for finned absorber plate in solar still application.

MATERIALS AND METHODS

This research was conducted experimentally by observing the phenomena that occurred directly. A total of five types of specimens have been selected and processed to be suitable for performance comparison in mass transfer test. Two different types of fine aggregate was chosen. The first type of aggregate was conventional sand that gained from Lumajang mines. This sand is one of the most widely used sand in East Java region due to it's good quality As an effort to get a better conductivity, the ferrous sand was chosen as the second type of aggregate. Furthermore, the granular size of those two aggregate divided in to 0.125 and 0.250 mm. The concrete mixture ratio on each specimen used was 1:2 of cement and sand, respectively. Natural stone was used as a reference material. This comparison was conducted to obtain the performance of naturally formed porous media. Natural stone that used in this study was the black stone gained from Mt. Arjuno East Java. This type of stone usually used as the basic materials for temples and traditional mortar. Table 1 give the detail of materials used in this study.

In order to obtain the chemical compositionof each materials an XRF test was conducted. XRF test identifies the composition of elements in each specimen by analyzing the radiation emitted from electron dislocation. The emmited rays with a ranged amount of energy make a dislocation of electrons in each orbital skins. Each composition has a specific amount of energy requirement to dislocate its electron, thus, the data obtained from the sensor. Although, there were limitations that this test that only specifies few range of elements. This test was conducted in Central Laboratory University of Malang which used the PANalytical/Minipal 4 and the results are shown in Fig. 1-4.

Lumajang sand: There are four dominant compositions in Lumajang sand. That is Fe (37%), Ca (20%), Si (25%) and Al (10%). Physically Lumajang sand has the smoothness

Table 1: Details of specimens

Specimens	Aggregate types	Particle size (diameter) mm
A	Lumajang's sand	0.125
B	Lumajang's sand	0.250
C	Ferrous sand	0.125
D	Ferrous sand	0.250
E	Natural stone	-

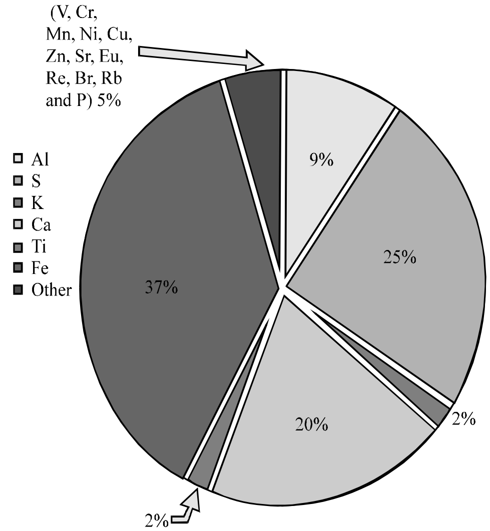

Fig. 1: Chemical composition of Lumajang sand

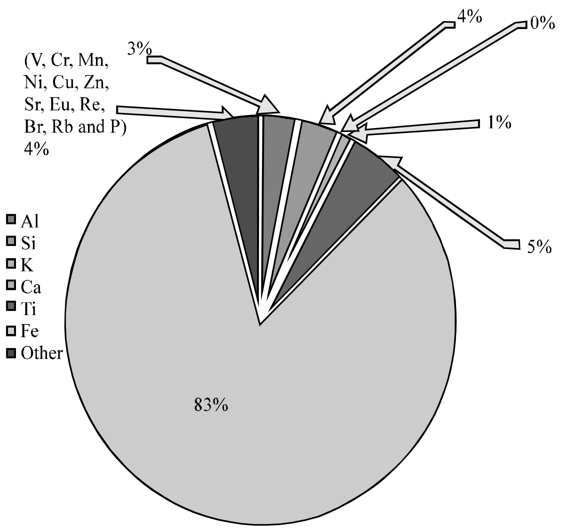

Fig. 2: Chemical composition of ferrous sand

index of 2.73 which satisfies the SII 0052-80 standards. The yellow organic compound that fulfill the requirement of SII 007-75. It's mud content which has the value of 1.69% still below the maximum limit of SII 0052-80 (5% max limit). This sand still counted in region 4, thus, make Lumajang sand is included as a fine granular sand according to SNI 03-2843-1993.

Ferrous sand: As could be seen in Fig. 2, the most dominant compound of ferrous sand was Fe (83%). The Fe concentration of ferrous sand was the greatest among the three materials used in this study. This made the

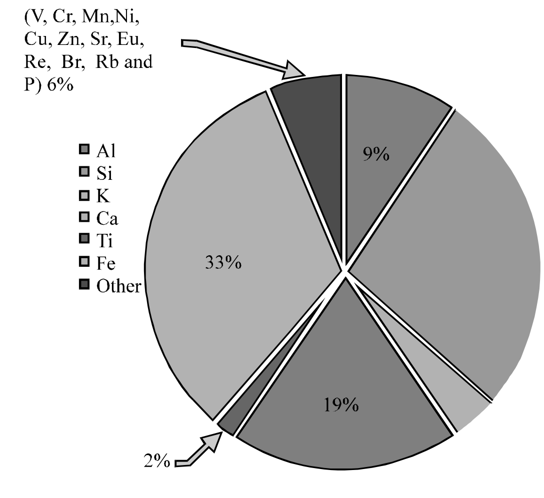

Fig. 3: Chemical composition of natural stone

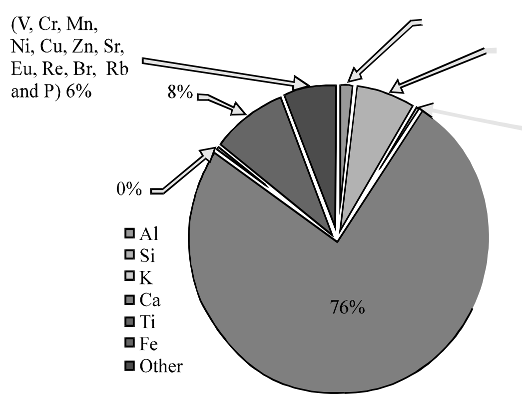

Fig. 4: Chemical composition of portland cement

specimens which contained ferrous sand as its aggregate most likely has a greater value in thermal conductivity.

In general, ferrous sand has a black color, specific weight of 1.8 ton/m^3, particle size of 1/16-2 mm and has a high magnetic potential.

Natural stone: The natural stone used in this study generally had a similar composition with Lumajang sand. The main differences in both materials was the natural stone had fewer Fe concentration than Lumajang sand. This natural stone had more variety in composition than Lumajang sand.

Portland cement: The cement materials was originally produced by PT. Semen Gresik. Based from the data, physically, it has a specific weight of 1.31 g/cm^3 which satisfy the requirement of SNI 0013-77. Figure 4 shows the most dominant chemical compound of Portland cement was Ca 76%.

The sea water used in this study wasgained from District Kraksaan of Probolinggo. The specifications of the seawater is as follows: pH value between 7:26 to 7:05, salinity between 10-20 ppt, TSS ranged from 15-19 ppm, Na ranged between 3076.5-6153 mg/L, Cl ranged between 5529-11058 mg/L, mg ranged between 370.5-741 mg/L, SO_4 ranged from 0.765-1.53 mg/L. The composition of the salt from this seawater is as follow: Na 17.79±0.11%, ±1.17 Mg 0.01%, Cl 61.4±0.23%, SO_4 0.7309±0.0013% (Tri, 2011).

Each specimen was shaped equally with the dimension of 5×1×10 cm. These size given to satisfy the geometry of finned absorber plate in solar still. Several test was conducted to get the mass flow characteristic of each specimens. The surface characteristic were photographed with macro photo test with the 50× magnification. The macro photograph was taken on each specimen's surface. This data test was performed to find the number of pores and pore's diameter in porous media. The process of image taking was performed randomly four times at both sides of porous mediaspecimen. From the results of the macro photographs, the image was taken then processed by using Image G Software.

Porosity data was taken in several steps. Every specimenhas an equal Volume (V), namely; 50 cm^3 or 50×10^{-6} m^3. Each specimen was heated in an oven with a temperature of ±100°C for 24 h and then the final mass of specimens observed. This step aims to find the dry mass (m_{dry}) of the specimen in which the specimen is has the moisture content of 0%. The next step wasto soak the specimen in a pure water for 24 h which then the data of fully saturated weight was observed (m_{wet}). Due to the water fluid (ρ_w = 1000 kg/m^3) that filled the empty spaces in porous media, the volume of the empty spaces could be specified. The calculation of porosity (ε) obtained by using the following equation (Nugroho, 2010):

$$\varepsilon = \frac{(m_{wet}-m_{dry})\times\frac{1}{\rho_w}}{V}$$

Where:

ε = Porosity of porous media (%)
m_{wet} = Fully saturated mass (kg)
m_{dry} = Dry mass of specimen (kg)
ρ_w = Density of water (kg/m^3)
V = Volume of specimen (m^3)

Experimental test scheme of mass transfer in porous media is shown in Fig. 5. The specimen is placed in a glass container with a pedestal at the base. The sea water flowed from a scaled reservoir. The seawater depth inside the container is set to remain at a constant height of 1 cm

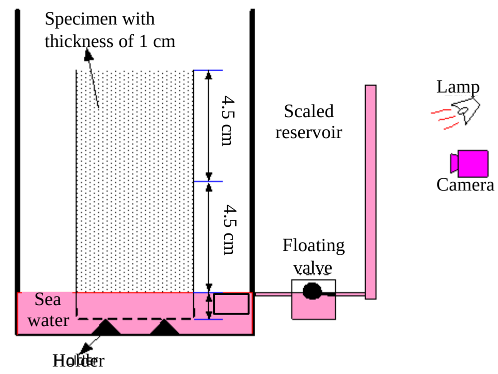

Fig. 5: Schematic of the experimental apparatus

from the bottom of the specimen. This setting was conducted using a floating valve. Thus, even though the water is absorbed by the specimen, the amount of water inside the container will always be at a constant height. Therefore the area of specimen that submerged in water was 5×1 cm^2. By using the measuring scale in reservoir, the amount of water entering the porous media could be defined.

The amount of absorbed water in each specimen was recorded at intervals of 5 min. The test was held for 12 h in every specimen. If there were no more decreasing water level in the reservoir, it can be concluded that the amount of absorbed sea water inside the porous media has reached its maximum limit. The entire specimen showed there were no specimen that require more than 12 h to achieve the maximum limit.

RESULTS AND DISCUSSION

Surface characteristic of porous media: The results of the macro photograph by image processing software Image G are as follows.

Figure 6 only showed one of the image processed in each specimen. Dark /red marks on each images shows the area of pore holes in specimen's porous media. The area of each image in Fig. 6 was 24×18 mm.

From the image processing results, some data could be obtained in order to analyze the surface characteristic of porous media. The surface characteristic data such as the number of pore holes, the total area of the pore hole, the mean area ofthe pore holes and the percentage of pore area to the total area of the photograph image of the specimen. The data collected was the mean value of total of 6 image processed in each specimen.The details of the surface characteristics of porous media are presented in Fig. 7-10. The details of each specimen can be seen in Table 1.

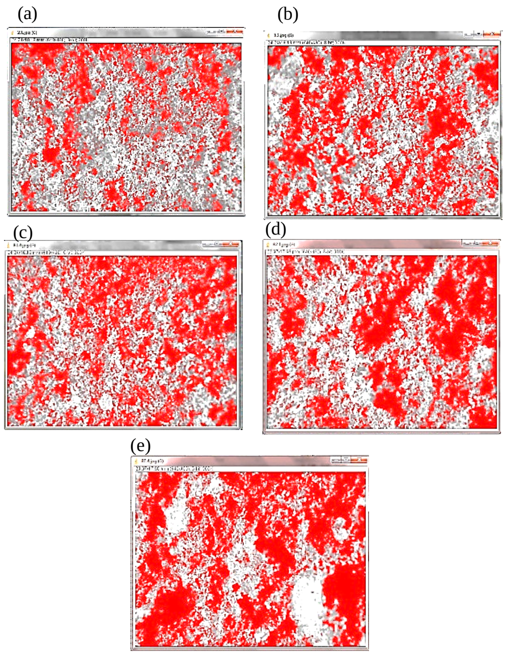

Fig. 6: Image processing result; a) Specimen A; b) Specimen B; c) Specimen C; d) Specimen D and e) Specimen E

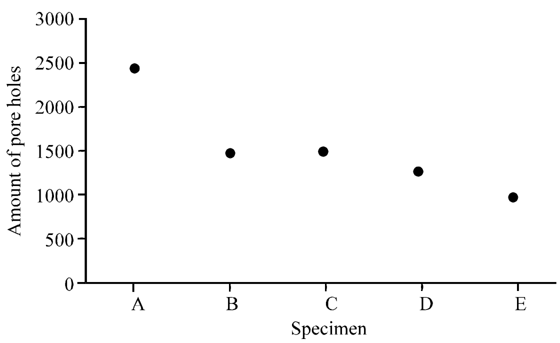

Fig. 7: Number of pore hole in each specimen

Figure 7 shows that the largest number of pore holes was obtained in specimen A with the value of 2473. While the smallest number of pore holes wasgained in specimen E with the amounts of 996 holes. There is a decrease in the number of holes in the specimen with a largerparticle size of aggregate 0.250 on each aggregate's type. This is because the smaller aggregate's particles sizemakes the possibility of the formation of pores in the concrete hole tends to be greater. Even, so, it is possible that the specimen with a grain size of 0.250 aggregate can have a radius larger holes.

Figure 8 shows the largest mean of pore holes area gained in natural stone specimen with a value of

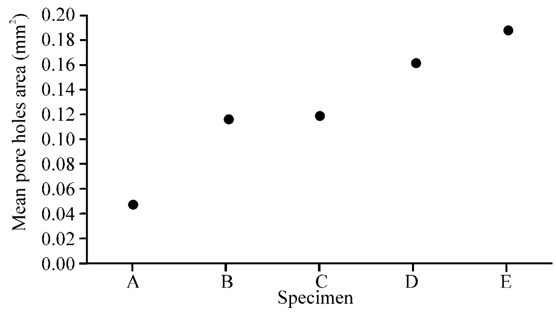

Fig. 8: The mean of pore holes area in each specimen

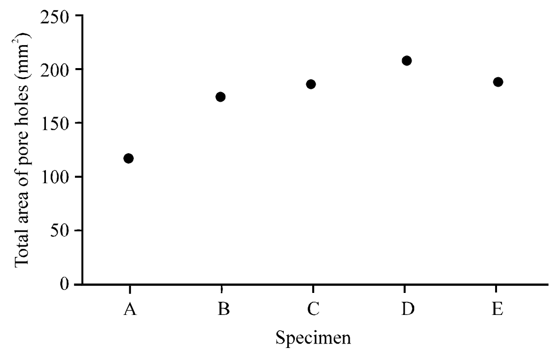

Fig. 9: Total area of pore holes in each specimens

0.189 mm^2. While the smallest pore holes area gained in specimen A with an average area of 0.047 mm^2.

The concrete specimen with ferrous sand as aggregate has a bigger mean pore holes area if compared with Lumajang sand specimen. Ferrous sand has a heavier mass than Lumajang sand, thus, make the distribution of particles not evenly spread. As it could be defined that the larger aggregate particle size would resulted in a bigger pore hole area that formed.

As could be seen in Fig. 9, the largest total area of pore hole gained in specimen D with the amount of 206.564 mm^2. Meanwhile, specimen A has the smallest total area with a value of 117 035 mm^2.

Along with the largerparticle size of aggregate in every similar type of aggregate affect the total area of pore holes to be greater. This is because along with the larger grain size, the space between the particles would also getting bigger. Although, the smaller particle size aggregates has a higher amount number of holes, it does not guarantee that the total area of the holes also increased.

Figure 10 depicts the percentage of the total area of the holes are formed in total area of the macro image photograph. As it could be seen the accumulation of the largest percentage of hole area obtained on specimen

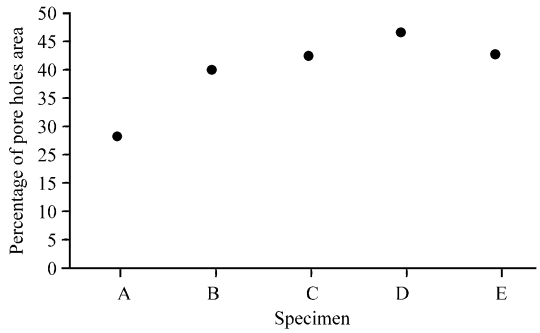

Fig. 10: Percentage of pore holes area in each specimen

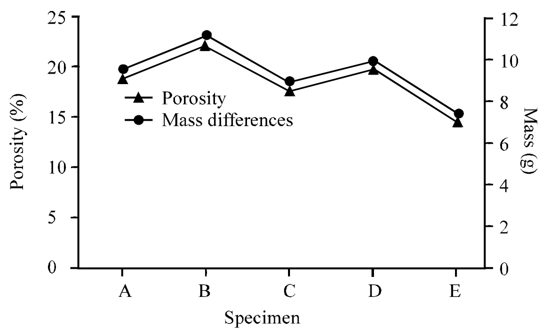

Fig. 11: Porosity test result and mass differences obtained in each specimen

D with the amount of 46.864%. While the smallest percentage owned by the specimen A which is equal to 26.55%. There is an increase in the percentage of area of holes along with increasing particle size of aggregate used in concrete mixture. Natural stone has the second largest percentage of hole area that is 42 708%.

In all of the data obtained from the macro photographs, specimens with greater particle size of aggregate yield a larger hole area. But in terms of the amount of holes, a specimen with a smallerparticle size aggregate will produce a bigger number of holes.

Liquid capillary mass flow and sorptivity: Figure 11 shows the porosity test results on each specimen. If the results of data processing macro image obtained on the surface of porous media characteristics, the porosity test can show the percentage volume of cavityinside the porous media. Figure 11 shows the value of porosity tends to be greater asgrain size aggregates also larger. The natural stone specimen has the smallest porosity namely by the amount of 14.6%. While the specimens with the highest porosity owned by specimen B with value of 22.4%.

Along with the larger pore size the value of porosity also getting higher. This is due to the cavities that formed between each particles was bigger in a larger pore size.

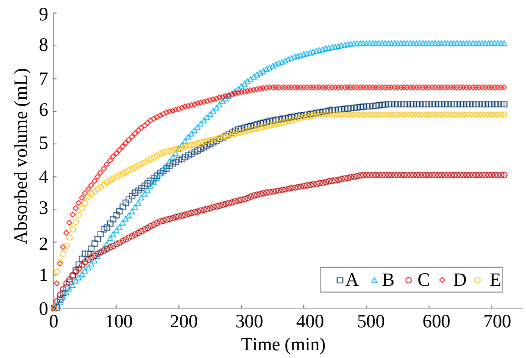

Fig. 12: Volume of absorbed seawater in each specimens

Concrete with Lumajang sand has a higher porosity than the ferrous sand in each same particle size. it is because of the ferrous sand has heavier mass than Lumajang sand. This resulted in a denser formation of concrete in ferrous sand specimens. Beside that the magnetic properties of Fe compound also has an attractive force between each particles which could lead to a more compacted concrete formation.The relationship of porosity and mass differences was in a linear tendencies, along with higher porosity the mass flow also tend to get higher.

Figure 12 shows the amount of decreasing volume in reservoir over 12 h of observations. The data retrieved in every 5 min. It can be seen from Fig. 12, water absorption occurs only within a certain time to reach itsmaximum.

Each specimens tends to have different maximum value due to its different structure. The time required to reach its own maximum absorbed seawater also varies. The largest total volume of seawater absorbed obtained in specimen B with a value of 8.05 mL. While the smallest volume of absorbed seawater obtained in specimen C with a total volume of 4.05 mL. The shortest time required to reach maximum volume absorbed is obtained in specimen Dwith a value of 345 min. While the specimen that takes the longest time to reach the maximum volume absorbed were obtained in specimen A with a value of 535 min.

In both type of aggregate, the larger particles size leads to a higher amount of absorbed seawater. Higher porosity makes the value of permeability also getting higher. The smaller contact angle could increase the amount of absorbed seawater.

From Fig. 12, it could be seen that theoretically, the natural stone specimen has a low porosity and so does permeability, however, the amount of absorbed sea water of this specimen still higher than specimen C some parameters that could not determined in this research such as interconnectivity between the channels has a significant role to this phenomenon. It is

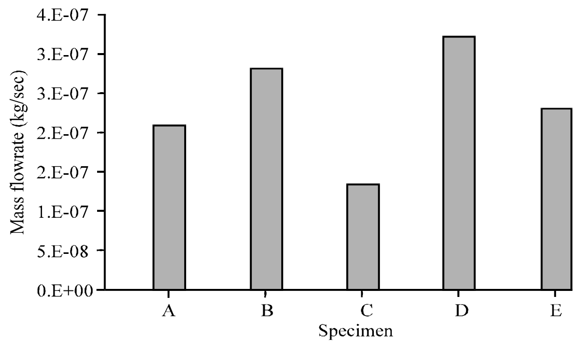

Fig. 13: Mass flow rate data of each specimens

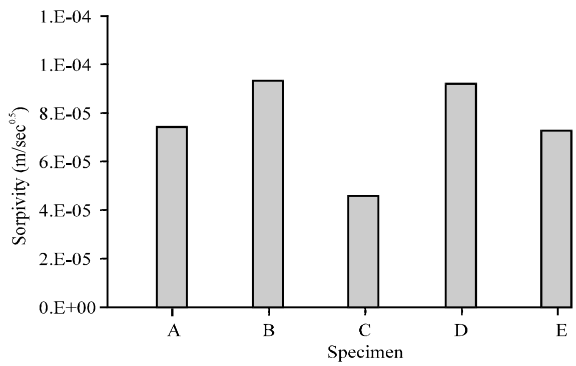

Fig. 14: Sorptivity coefficient of each specimen

expected that natural stone specimen has a high interconnectivity because of its channels was developed naturally.

In overall concrete materials, the Lumajang sand specimens has higher absorbed seawater than ferrous sand specimens. From the surface characteristic and porosity data, the concrete materials has higher value than natural stone specimen. However, it could be defined that the concrete materials has a less interconnectivity between it's empty spaces than natural stone specimen.

Figure 13 depicts the mass flow rate data of each specimen. The data was obtained from the accumulated total volume of absorbed seawater divided by the total required time to reach the maximum absorbed seawater. Specimen D has the highest mass flow rate with the value of 3.25×10^{-7} kg /sec. While the lowest flow rate owned by specimen C with a mass flow rate of 1.36×10^{-7} kg/sec. Although, the amount of absorbed seawater of the specimen B is higher than specimen D, the specimen D has a shorter time to reach its maximum absorbed seawater. It is estimated that the capillary channel condition of the specimen D is not entirely connected between each other. This causes the flow of sea water inside the pores of the capillary channel of specimen D cannot flows fluently. It was shown by specimens of natural stone whereas from the observational data can be predicted that the capillary channel on the inside are connected to one another, so that the flow of sea water can smoothly flow in the sorptivity coefficient was calculated using equation 6. As could be seen in Fig. 14, the soprtivity coefficient of each specimen has a similar trend with its mass flow rate. The highest sorptivity was obtained in specimen B with the value of 9.58×10^{-5} m/sec$^{0.5}$. While the lowest sorptivity was obtained in specimen C with the value of 4.70×10^{-5} m/sec$^{0.5}$.

The required time and the amount of seawater absorbed determine the sorptivity value. Thus in sorptivity coefficient, the maximum absorbed seawater played more significant role than the required time. This makes the specimen B has a higher sorptivity coefficient than specimen D although specimen D has a higher mass flow rate.

CONCLUSION

Based from the experimental data observation, some conclusion of this study is as follow: the largest amount of pore holes obtained in concrete with Lumajang sand and aggregate size of 0.125 mm with the amount of 2473. The natural stone specimen has the largest mean pore holes area with the value of 0.189 mm^2. The largest total area of pore holes obtained in concrete with ferrous sand and aggregate size of 0.250 mm specimen with the amount of 206.564 mm^2. Smaller aggregate's particle size resulting a lower value of total pore holes area but it has a larger amount of holes.

Due to the amount of Fe and heavier mass of ferrous sand aggregate leads to a denser and more compact structure of concrete. Which make a smaller porosity and pore radius than the Lumajang sand specimens. The highest porosity obtained in concrete with Lumajang sand with aggregate size of 0.250 mm specimen with the value of 0.224%.

The largest volume of absorbed seawater and sorptivity coefficient was also obtained in concrete with Lumajang sand with aggregate size of 0.250 with the value of 8.05 mL. and 9.58×10^{-5} m/sec$^{0.5}$, respectively. However, concrete with ferrous sand with aggregate size of 0.250 has the highest mass flow rate with the value of 3.25×10^{-7} kg/sec.

Along with the smaller pore radius and larger porosity leads to a higher mass flow rate due to the larger capillary force. However, the interconnection between the channels also has a significant role in mass flow rate value which occurred in natural stone specimen.

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