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Evaluation of Porosity of Cement Paste Ring in Rebar Shaked-Reinforced Concrete

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***Abstract* - One of the major causes of corrosion in reinforced concrete is a porous zone at the Interfacial Transition Zone (ITZ) of reinforcement and Concrete due to poor compaction, high porosity and high bleeding. The compaction using Rebar shaker has proved to improve compaction and to reduce porosity at ITZ as it increases bond and adhesion of rebar and concrete. In this article, it has been concluded that the CPR reduces porosity at the ITZ and the zone surrounding the CPR has lower porosity. The assessment of porosity behavior which is important in evaluation of suitability of Cement Paste Ring (CPR) in combating corrosion is being discussed. During the assessment the porosity was determined for the CPR of the Core Drilled Hollow Cylindrical, and the results were checked by determination of porosity of the zone covering the outer side of CPR and, by the Measuring of fluctuation in Porosity (from Outside towards Inside). Assessment was done for various concrete strengths, CPR thickness and by varying w/c ratio**.

Keywords*: *Rebar shaker; Cement Paste Ring; Porosity; corrosion; Interfacial Transition Zone

I. INTRODUCTION

The bond between concrete and steel reinforcement at the Interfacial Transition Zone (ITZ) is normally very porous, hence it promotes corrosion due to ingress of harmful chemicals. This weak and porous zone could be due to insufficient compaction, accumulation of bleeding water (higher effective w/c ratio) hence a more open - porous structure (Weiss et al., 2009; Munns et al, 2010). Therefore, compaction, porosity and bleeding at ITZ are vital for controlling corrosion. For most of the deteriorating processes, the permeability of the concrete is a key factor governing the rate of deterioration. (Gjørv, 2009). Permeability controls the rate of ingression of harmful chemicals diffusion. Low permeability may be attained by using a low water-to cementitious materials ratio and proper compaction (Nader 2008). Proper compaction can be achieved by rebar shaking technique. Rebar Shaking is a process of turning rebars into a vibrator (Bennet et al., 2003). This practice leaves steel bars enveloped by cement paste in other words; it creates a paste ring around rebar as shown in Figure 1. The cement paste ring (CPR) is synonyms of Concrete Paste Ring, in reality this zone is comprised of cement, fine sand, fine particles of aggregates and water; it is not just only cement and sand as the word depicts.

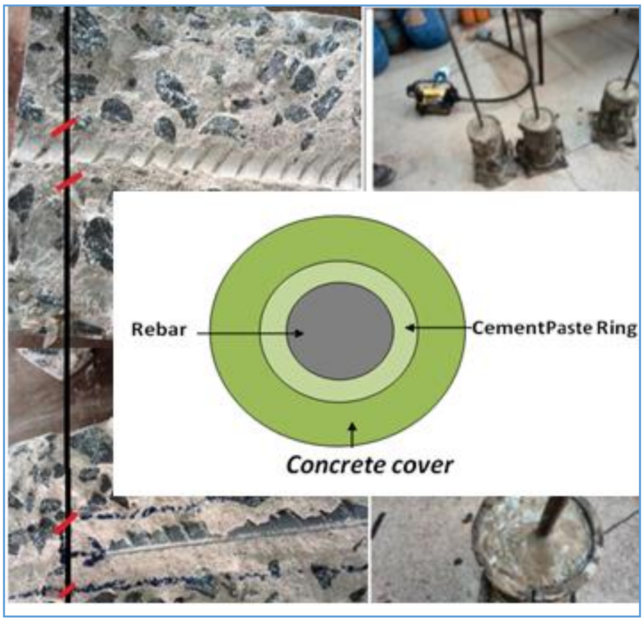

Figure 1: Sample Preparation and schematic diagram of cement paste ring**.**

Permeability is considered to be the key to the durability of concretes in various aggressive environment. It has been widely accepted that control of the permeability of concrete is more important than control of the chemistry of cement (Khatri, 1997). Consideration of low permeability to ensure durability is included in British Standard BS 5328, which states that permeability is ‘‘governed by the constituents, their proportions and the procedures used in making concrete’’. A relatively low w/c in cement paste does not necessarily mean a reduced permeability because of the significant influence of aggregates’ (Neville, 2004). Permeability of concrete is influenced by two primary factors porosity and interconnectivity of pores in the cement paste and micro-cracks in the concrete, especially at the paste–aggregate interface. On the other hand, porosity and interconnectivity are controlled mainly by the w/c ratio, degree of hydration, and the degree of compaction (Banthia, 2005 and Mehta and Monteiro, 2005). Studies and experience gained by using ordinary concrete have shown that concrete durability is mainly governed by concrete porosity and the harshness of the environment (Dvorkin, 2006)

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With respect to durability, which is the ability of concrete to resist various forms of deterioration is often related to its impermeability. Analysis of the sources of porosity and its connectivity can frequently provide the means to understand the mechanisms by which aggressive species can intrude concrete. This is because the pore structure defines the paths along which liquid or vapor preferentially moves. (Mehta and Monteiro, 2005)

Therefore, it has been suggested that the pore size distribution, not the total capillary porosity, is a better criterion for evaluating the characteristics of a hydrated cement paste. In all cases, it is the effective porosity, which is related to the degree of continuity of the pore system that significantly affect the transport properties of concrete (Mobasher, 2009). However, pore volume resulting at different water/cement ratios and degrees of hydration, does not uniquely define the pore system and thus is not uniquely related to the permeability. (Ramachandran, 1973). It is at this background that study of porosity becomes significant.

A. Review on Porosity

The prolonged-curing or moist state is a preferred situation for controlling of cracking due to shrinkage, as it hinders the movement of interlayer water in and out of the laminated structure of the gel particles (Soroka, 2004). This also suggests that there is no possibility of bleeding (Domone, 2003) at the interface of CPR and reinforcement. The active constituent of concrete is cement paste and the performance of concrete is largely determined by the cement paste

Capillary porosity is determined by drying a concrete sample and refilling the empty capillary pores with a dense organic liquid. Concrete is a porous material containing a system of pores covering a wide range of pore sizes. Pores can be found within the aggregate particles, and also between the particles if the intergranular voids are not completely filled with cement paste (Newman 2003).

The paste's porosity has different kinds of pores that which are;

i. Gel pores, in a size not much larger than a few times the size of a water molecule. These pores are responsible for most of the volume changes of concrete associated with gain or loss of water (drying shrinkage, swelling and part of the creep).

ii. Capillary pores, resulting from the space originally occupied by the water of the mix that has not been filled with hydration products. There are small capillary pores and larger capillary pores.

The main tools to modify the pore structure of concrete are; water/cement ratio that modifies volume and size of capillary pores, cement content which modifies volume of gel and capillary pores, and the use of special well graded aggregates. Studies shows that porosity and pore size distribution mainly affect some physical and mechanical properties of hardened cement pastes. Curing conditions as well as composition of the pastes in particular mineral admixtures influence total porosity and pore size distribution (Dhir and McCarthy 2006). The fine particles of sand at the CPR zone may reduce porosity at greater percentage.

II. EXPERIMENT AND ANALYSIS OF RESULTS

The Samples of concrete strength 20MPa with w/c ratio of 0.4 were prepared. The granitic aggregate and fine aggregate used had absorption less than 0.4 percent. Thickness of Cement Paste Ring is corresponding to vibration duration and is ranging from 5mm to 10mm.

A. Test 1: Porosity Determination for Core Drilled Hollow Cylindrical of CPR

Core drilling machine was used to extract some samples (7cm Height, 2.5cm outside diameter) from the concrete core containing the cement paste ring (CPR) as shown in Figure 2, where by steel rebar was replaced with hard PVC pipe in order to allow smooth porosity examination of the CPR.

Figure 2: Hollow cylindrical concrete samples

The idea behind was to minimize the effect of the bulk concrete on the porosity by reducing the quantity (thickness) of concrete cover attached to the surface in question i.e. the CPR. The thickness of concrete cover around the CPR was reduced up to an average of 5-7 mm (0.5cm).

I. Methodology

The methodology adopted to find the porosity require the determination of *total volume of the* sample (bulk volume of the sample Vb) and effective pore volume (Vp). So the procedures are based on the finding of these two values as follows:

$$\phi = \frac{V_p}{V_b} \qquad (1)$$

where: ϕ is porosity, V_p is volume of pores, and V_b is bulk volume of the sample.

So it is required to measure the two volumes in order to have the porosity which is the fraction of the bulk volume of the material occupied by voids.

The methods used are:

(i) *Fluid saturation method*; for determination of pore volume, where by samples are dried in an oven up to 120°C for 24 hrs. In order to evacuate air and

moisture then saturated in water for 24hrs or more in order to achieve total saturation of the samples, this in turn provide the volume of pores through equation (2)

$$V_p = \frac{W_{sat} - W_{dry}}{D_w} \quad (2)$$

where: W_{sat} is weight of soaked sample, W_{dry} is weight of dry sample, and D_w is fluid density and for water D_w = 1.01g/cc.

(ii) *Volumetric displacement method*; for determining Bulk volume of the samples, and this is measured by observing the change in volume level when the sample is totally submerged in fluid (water), this shown in equation 3.

$$V_b = f_{0-} f_i \quad (3)$$

where: Vb is bulk volume, f_0 is final water level, and f_i initial water level

The following procedure was adopted.

(a) Five cylindrical samples were core drilled, resulting into five samples (denoted as **S,** see figure 2), weighed and original weight were obtained, as shown in *Table I (a).*
(b) Samples were cleaned, then put into an oven at 120°c for 24hours (dehydration process) in order to evacuate all air and moisture trapped in the pores of the samples. Then weighed after and dry weight of samples were recorded, as shown in *Table 1(a).*
(c) After 24hours in an oven, samples were left to cool at room temperature then submerged into curing tank for another 24hours so as to undergo saturation process (fluid saturation method), then weighed after to obtain weight for soaked samples. The results are shown in *Table I (b).*
(d) After some time, the samples were further covered with paraffin, submerged into the graduated (measuring) cylinder for determination of the bulk volume of each sample (volumetric displacement method). Results are shown in *Table I (a).*

With the aid of equation (1), porosity was calculated, as shown in *Table 1(c).*

II. *Analysis of Results*

TABLE I (a): RESULTS FOR DETERMINATION OF BULK VOLUME BY VOLUMETRIC DISPLACEMENT

Sample notation	**Original weight**	**Dry weight after 24hrs**	**Initial vol. level**	**Final vol. level**	**Level difference/Bulk Vol. Vb (cc)**
S1	38.41	36.28	100	119	19
S2	35.82	33.91	100	118	18
S3	37.68	35.76	100	118	18
S4	45.28	42.95	100	122	22
S5	82.20	77.79	800	845	45

TABLE I (b): RESULTS FOR DETERMINATION OF VOLUMES OF PORES BY FLUID SATURATION

Sample notation	Dry weight (after 24hrs)	Soaked Weight 24hrs	Weight difference/Weight of pores	Volumes of pores (cc)
S1	36.28	38.25	1.97	2.85
S2	33.91	35.65	1.74	2.42
S3	35.76	37.82	2.06	2.60
S4	42.95	45.19	2.24	3.41
S5	77.79	81.05	3.26	5.57

TABLE I (c): ESTIMATE OF POROSITY

Sample notation	Volume of pores Vp (cc)	Bulk volume Vb (cc)	Porosity	Porosity %
S1	1.97	19	0.10	10
S2	1.74	18	0.10	10
S3	2.06	18	0.11	11
S4	2.24	22	0.10	10
S5	3.26	45	0.07	7
Average porosity			0.10	10

From *Table I(c)* above the average porosity is 10%. The lower value being 7% and highest value being 11%. The standard deviation for porosity value for this experiment is 1.37, the mean value is 10

B. Test 2: Determination of Porosity by covering the concrete cover attached to CPR

Modification of the idea was made by minimizing the effect of the rest of the concrete on the porosity by covering it with a water resistant sealant (silicon sealant). The outer part of the concrete samples was covered to the thickness of approx. 1mm to 2mm hence exposing only the surface of interest (CPR) as shown in Figures 3(a) and 3(b). This then allowed to find the porosity of the CPR only, since the amount of fluid (water) absorbed is due to the pores (effective pores) present on the surface in question, through this hypothesis the approximate porosity of the CPR was obtained.

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Figure 3(a): Water resistant sealant (1mm to 2mm thickness)

Figure 3(b): Samples under curing and reweighing process

I. *Methodology*

Methodology adopted was as stated in **2.0** above. The porosity value of this method is as shown *Table III (c).*

In determining the porosity, the following procedure was adopted

(a) Three whole cylindrical samples were core drilled resulting into five small samples as shown in *Figure 2.*

(b) The resulted five clean and dry sample covered with paraffin were immersed into the graduated (measuring) cylinder for determination of the bulk volume of each sample by the *Volumetric Displacement Method*. Results are shown in *Table II (a)*

(c) Further, the samples were dried in then put into an oven at 120 °C for 24hrs (dehydration process) in order to evacuate all air and moisture present in the pores of the samples. Then weighed after, view results in *Table II (b)*

(d) Then samples were covered with water resistant sealant as shown in *Figure 3(a)*, to prevent the absorption of fluid(water) by unnecessary surface (i.e. the concrete cover) leaving only the CPR exposed to the fluid(water) to be soaked in the process to give us the approximate values of porosity (*effective porosity*). The samples were left to undergo curing on free air for 72 hrs.

(e) The samples ware then weighed in order to determine the increase in weight due to the water resistant cover before being soaked into the curing tank filled with water for 24hours ***(Fluid Saturation Method)*** as shown in *figure 3(b)*. After 24hours they were reweighed as seen in *Figure 3(b)*, and the results tabulated in *Table II (b).*

II. *Results analysis*

TABLE II (a): DETERMINATION OF BULK VOLUME BY VOLUMETRIC DISPLACEMENT

Sample notation	Original weight (g)	Dry weight after 24hrs(g)	Initial vol. level	Final vol. level	Level difference/ Bulk Vol. Vb (cc)
S1	37.36	35.23	100	118	18
S2	37.13	35.22	100	117	17
S3	36.87	34.95	100	116	16
S4	37.88	35.55	100	119	19
S5	40.16	35.75	200	219	19

TABLE II (b): DETERMINATION OF VOLUMES OF PORES BY FLUID SATURATION

Sample notation	Dry weight with cover(g)	Soaked Weight with cover 24hrs(g)	Weight difference/ Weight of pores	Volumes of pores (cc)	Sample notation
S1	38.71	40.06	1.35	1.34	S1
S2	38.25	39.28	1.03	1.02	S2
S3	38.22	39.39	1.17	1.16	S3
S4	39.35	41.02	1.67	1.65	S4
S5	41.74	43.06	1.94	1.92	S5

TABLE II (c): ESTIMATE OF POROSITY

Sample notation	Volume of pores Vp (cc)	Bulk Volume Vb (cc)	Porosity	% Porosity
S1	1.34	18	0.07	7.4
S2	1.02	17	0.06	6.0
S3	1.16	16	0.07	7.2
S4	1.65	19	0.09	8.7
S5	1.92	19	0.1	10.1
Average Porosity			0.08	7.9

The standard deviation for porosity % for this experiment is 1.4, the mean is 7.9%

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C. Test 3: Measurement of Fluctuation in Porosity (from Outside to Inside)

The determination of porosity from outer layer to inner layer could be beneficial to understand the porosity behavior of concrete sample with CPR ring. It also helps to understand layers of concrete near the CPR.

I. Methodology

Small almost rectangular parts were cut out from two cylindrical concrete samples (rebar-shaked sample and cured for 28 days) which included the surface of interest (cement paste ring) as shown in *Figure 4*.

Each sample was carefully cut/divided into three part namely **S**, **M** and **N** as shown in *Figure 4*.

Where by: **S** denotes the outer part, **M** the middle part and **N** is for the inner part (containing paste ring).

Figure 4: Section of Samples for porosity determination

The fluid saturation method and volumetric displacement method were used to determine, the bulk volume of the sample (Vb) and the results are shown in *Table III (b)*. For the effective pore volume (Vp), the respective results are shown in *Table III (a)*. The porosity values of this test are shown in *Table III (c)*.

a) In the fluid saturation method; for determination of pore volume (Vp), the samples were dried in an oven at 120°C or 24 hrs to evacuate air and moisture, weighted, saturated in water for another 24 hrs, in order to achieve total saturation of the samples. Results obtained are as shown in *Table III (a)*.

TABLE III (a): VOLUME OF PORES

Sample notation	Weight dry (g)	Weight saturated(g)	Weight difference(g)	Volume of pores (Vp)
S_1	39.85	41.58	1.73	1.71
S_2	30.02	31.89	1.87	1.85
M_1	56.34	59.43	3.09	3.06
M_2	34.43	37.48	3.05	3.02
N_1	11.10	12.04	0.94	0.93
N_2	19.73	21.52	1.79	1.77

b) In the volumetric displacement method; for determining Bulk volume, the samples were coated with paraffin to prevent the penetration of the fluid into the pore spaces of the samples. Results are as shown in *Table III (b).*

TABLE III (b): BULK VOLUMES OF SAMPLES

Sample notation	Initial volume level (ml)	Final volume level (ml)	Level difference /Bulk volume Vb (ml)
S1	80	99	19
S2	80	95	15
M1	150	180	30
M2	150	180	30
N1	40	58	18
N2	50	65	15

TABLE III (c): POROSITY VALUES

Sample notation	Vp (cc)	Vb (cc)	Porosity	Average porosity
S_1	1.71	19	0.09	0.11
S_2	1.85	15	0.12	
M_1	3.06	30	0.10	0.10
M_2	3.02	30	0.10	
N_1	0.93	18	0.05	0.08
N_2	1.77	15	0.12	

From the results above we can see that there is no big difference of porosity (effective porosity) as we approach the steel rebar that was vibrated. So it can be expected that surface of interest (cement paste ring) have more elevated value of effective porosity compared to the rest of the concrete. This lead to series of experiments to determine the fluctuation of porosity from the cover to the inner most layer, i.e., at ITZ of rebar and CPR. The slice of a cylinder was prepared, cut into small rectangular parts of 2cm x 4cm x 5cm as shown in *Figure 5*. Seven samples from different cylindrical concrete samples were prepared, the effective bulk volume, pore volume and average porosity were found using the same methodology as above, and recorded in the *Table III (d)*.

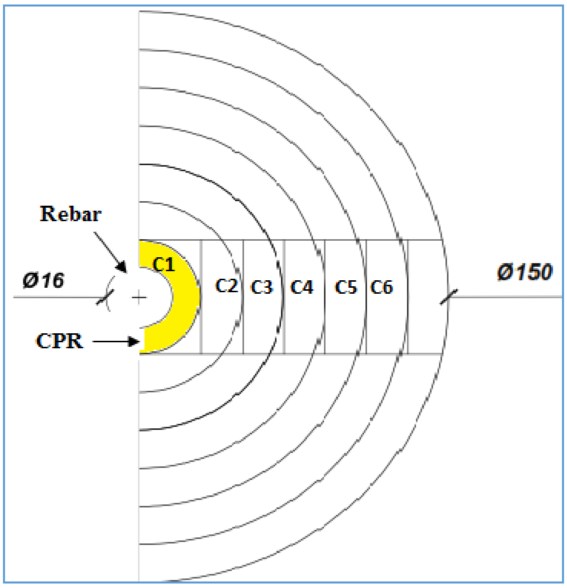

Figure 5: Cut sections from cylindrical sample.

TABLE III (d): AVERAGE POROSITY OF CUT SECTIONS

	Porosity (%)							Average Porosity (%)
Samples	S1	S2	S3	S4	S5	S6	S7	
Cut Section								
C1	8	8	8.3	8.4	7.9	9	7.6	8.17
C2	7.3	7.1	7.5	7.3	7.2	7.5	7.2	7.30
C3	10.2	11.3	11.9	11.3	10.3	10.2	11.2	10.91
C4	12	12	12.9	13.5	13.2	13.1	11.2	12.56
C5	12	13	12	14	13	13	12	12.71

D. Test 4: Variation of CPR thickness, w/c ratio and strength

The experiments performed above were repeated by varying strength of concrete, w/c ratio and thickness of CPR and the results are as presented in *Table IV*.

TABLE IV: RELATION OF W/C RATIO, CPR THICKNESS, STRENGTH OF CONCRETE

Strength (MPa)	20				25			
w/c ratio	0.4		0.5		0.4		0.5	
CPR Thickness (mm)	10	6	10	6	10	6	10	6
Sample 1	7	7	7	7	7	7	7	7
sample 2	7	7	7	7	7	7	7	7
sample 3	7	7	7	7	7	7	7	7
Standard Deviation	1.5	0.5	1.5	0.5	1.5	0.5	1.5	0.5

III. DISCUSSION OF RESULTS

A. CPR, fine particles and compaction

The presence of fine particles and presence of saturation eliminate the formation of capillary cavities (Shetty, 2005). The fine particles and good compaction at CPR zone have reduced the porosity as depicted by the results of Test experiments 1, 2 and 3. However, it seems that the zone which is close to the start of CPR zone has lower porosity than CPR itself. This could be because of relatively finer aggregate, prolonged curing and higher amount of cement than in the interface of rebar and CPR.

Generally, there is a fundamental inverse relationship between porosity and strength of solids. The higher the porosity the lower the strength as shown in *Table IV*. Also the relationship between water-cement ratio and porosity is very important, though it does not depend on other factor. In this experiments thickness of CPR has influences on the porosity of CPR and the section adjacent to CPR. The effect of the water-cement ratio on the permeability and strength of concrete is generally attributed to the relationship that exists between the water cement ratio and the porosity of hydrated cement paste in concrete and the thickness of CPR. The thicker the CPR the slightly lower the porosity, and on the other hand the higher the strength attributed by lower w/c ratio the lower the porosity.

Compared to 30 to 40 percent capillary porosity of ordinary cement paste present in hardened concrete, the volume of pores in most natural aggregates is usually below 3 percent and rarely exceeds 10 percent. It is expected, therefore, that the permeability of aggregate would be much lower than that of the typical cement paste. This could be the reason why test experiment no.3, the section adjacent to CPR ring seem to have very low porosity because of presence of finer aggregates.

B. Porosity vs w/c ratio and permeability

The porosity of the paste is much higher due to incomplete hydration and the use of higher w/c ratio. The water cement ratio at the ITZ of rebar and CPR was determined and found to be 0.4 the same as of the bulk concrete. A high water/cement ratio will increase the capillary porosity and the rate of carbonation as seen in experiment no. 4. Generally, when the water-cement ratio is high and the degree of hydration is low, the cement paste will have a high capillary porosity.

With conventional cement pastes, the discontinuity in the capillary network is generally reached when the capillary porosity is about 30 percent for the w/c ratio ranging from 0.4 to 0.7, though water-cement ratio in most concrete mixtures seldom exceeds 0.7, theoretically, with most well-cured concrete mixtures, cement paste should not be the principal contributing factor to the coefficient of permeability of concrete, (Mehta P. K., 2013). Typically, about 30 percent capillary porosity represent a point when the interconnections between the pores have already become so tortuous that a further decrease in the porosity of the paste is not accompanied by a substantial decrease in the permeability coefficient, (A. Bonakdar, 2010). The physical count of pores using special tool will assist to confirm the interconnectivity of pores that will lead to permeability. All experiments have shown porosity of CPR ring and nearby zones are less than 12%.

IV. CONCLUSION

From the investigation carried out and discussion above, following are the conclusions

i. CPR has proved to reduce porosity at ITZ between rebar and concrete due to presence of fine particles and good compaction, adhesion of concrete paste on the rebar and prolonged curing.

ii. The Zone adjacent to CPR has lower porosity than CPR itself because this zone has higher presence of cement, relatively fine aggregates, optimal w/c ratio and good compaction.

iii. A properly consolidated, and cured concrete remains essentially water-tight as long as the micro cracks and pores within the interior do not form an interconnected network of pathways leading to the surface of concrete, and from the tests conducted above have revealed the porosity to be less than 18%, which maximizes the chance of pore discontinuity (Cook and Hover 1999, Justness 2009, Roy 1993) thus reducing permeability and hence increases durability chances of structure.

V. RECOMMENDATION

The most common method of analyzing porosity data is to determine pores networks, pore size distribution, pore radius and averaged pore size, further research and investigation using sophisticated tools such as Petrographic image analysis (**PIA**) is recommended.

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