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Experimental Study of the Effect of Cavities on the Load Capacity of Two-Way Reinforced Concrete Plates on Fixed Concrete Thickness

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Abstract. The study aims to determine the effect of cavities on the load capacity of reinforced concrete slabs when compared to massive reinforced concrete slabs that have the same thickness, with the hope of reducing the structure's weight and the use of concrete materials. The modified PVC pipes, as cavity formers, will be placed in the tensile area without reducing the flexural strength that is caused by the weak nature of concrete against tensile strength. The test is carried out on a full scale against 14 cm thick solid plates (PP-1), and hollow plates, which use modified PVC pipes (PB-2), with a cavity diameter of 7.6 cm that has the same thickness. The test uses joint supports on all four sides and the loading pattern is evenly distributed. All slabs are made, on the spot, of cast concrete with the same size and distance between the reinforcement. PVC hollow plate (PB-2) has the same effective thickness as solid plate but has 14% less concrete volume. The maximum load capacity on the solid plate (PP-1) is 522.66 kN and on the hollow plate (PB-2) is 444.33 kN. The melting capacity on the solid plate (PP-1) is 373,515 kN and on the hollow plate (PB-2) is 325,935 kN. Initial crack load capacity on the solid plate (PP-1) is 19.5 kN and on the hollow plate (PB-2) is 16.75 kN

1. Introduction

Hollow Core Slab technology is a technology that seeks to increase the efficiency of reinforced concrete slab structures. The technology aims to reduce the structure's weight and to save concrete material. The limitations of the Hollow Core Slab as a one-way slab have spurred various studies to find reinforced concrete slabs that are lightweight and can behave as two-way slabs. In 1990, Joergen Breuning invented a spherical hollow plate called the Bubble Deck. Bubble Deck is produced with a thickness of 230 - 600 mm. Slabs of this type are 30–40% lighter than solid plates of the same

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dimension, which generally have the same behavior as solid concrete slabs. The spherical hollow concrete plate can distribute forces better than Hollow Core Slab. It is because the three-dimensional shape of the cavity of the structure can cause the flow of forces to work better [1].

From 2003 to 2005, several researchers have developed alternative technologies for hollow concrete slabs. Aldejohann and Schnellencbach conduct a Biaxial Hollow Slab study where both types of slabs have cavities in the concrete in the tensile area, thereby reducing their weight [2]. In 2009, Kris Bayu Aji and Andry Soeharno researched spherical hollow plates with a cast-in-site system [3-4]. In 2013 La Ode Abdul Majid Muizu and Dyah Widiastri Intansari researched one-way hollow reinforced concrete slabs with a cast-in-site system, where the cavities were made by using bottles of drinking water. With the holes in the slab, the volume of concrete used will be less. It can reduce the cost of making concrete structures [5-6]. When the volume of concrete used decreases, the need for cement as the main material for making concrete will decrease. In the end, it will reduce CO_2 emissions in the air.

The purpose of the study is to determine the behavior and to compare the initial crack load, melting load, and the maximum load that occurs due to evenly loading on hollow concrete slabs and solid reinforced concrete slabs. Hollow reinforced concrete slabs have the same thickness as solid reinforced concrete slabs. The test method is the two-way plate testing with a uniform loading simulation. The expected benefit from the analysis is to reduce the use of concrete and to increase the use of lighter plates, which is caused by the presence of cavities in reinforced concrete slabs. Also, it is expected that the study can explain the effect of cavities on the loading.

2. Literature Review

2.1 Plates

Plates are horizontal plane elements of a structure that support both dead and live loads and transmit them to the vertical frame of the structural system [7]. A plate is a flat plane structure in which all the mid plane is flat. After experiencing a load perpendicular to it, or the bending moment, it will bend [8]. Plates are divided into 4 categories [9], namely:

a. Rigid Plates
   Thin plates that have flexural rigid. Rigid plates carry loads with 2D action, especially with internal moments (bending and twisting) and transverse shear forces that are generally the same as those of the beam.
b. Membrane
   Thin plates without bending stress that carries lateral loads by axial shear and centred shear forces.
c. Thick Plates
   Plates whose inner stress conditions resemble 3D continuous conditions.
d. Flexible Plates.
   A combination of a rigid plate and a membrane that carries external loads with a combination of the internal moment action, axial shear force, central shear force, and transverse shear force. The above plate categories are presented in Figure 1 below:

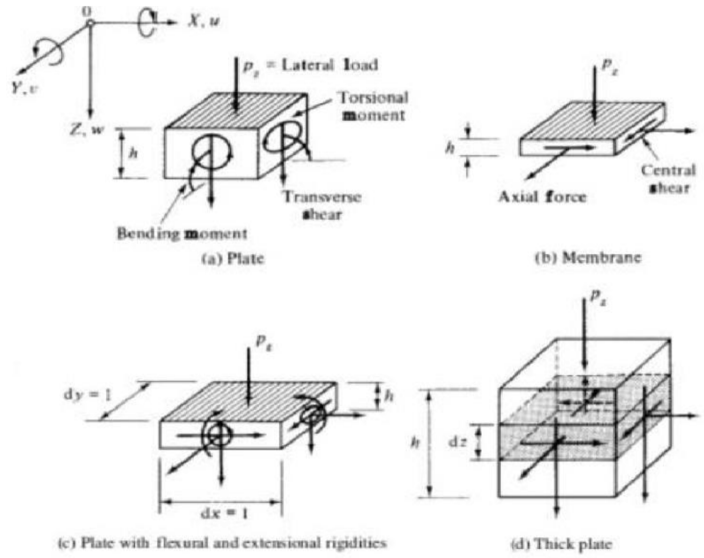

Figure 1. Inner Forces on Different Types of Plates

On a rigid plate, or a thin plate, with a smaller deflection than its thickness, a thin plate theory can be developed [8] with the following conditions and assumptions:

a. The load is perpendicular to the centre plane, or moment.
b. The material is homogeneous, isotropic and linear elastic.
c. The Bernuolli principle applies so that there is no shear deformation in the z-axis direction ($\gamma xz = 0$ and $\gamma yz = 0$).
d. The strain and stress on the z-axis are so small as compared to the x- or y-axes that they are negligible.

Based on the above requirements and assumptions, there is a consideration that all points contained in the plane perpendicular to the centre plane of the plate will experience the same displacement in the z-axis direction. Also, a linear relationship applies to the stress and strain of materials as follows:

$$\sigma x = (E/(1-v^2))(Vx+Vy) \ldots\ldots 1$$

$$\sigma x = (E/(1-v^2))(Vy+Vy) \ldots\ldots 2$$

$$\sigma xy = (E/2(1-v^2))(Vxy) \ldots\ldots 3$$

The above formula shows that the relationship between the stress and strain of the material is limited to the x-plane and y-plane only (two dimensions).

The thin plate theory assumes that the points that originally lie on a line normal to the centre surface of the plate will remain on the normal line after the bending occurs. The assumption ignores the effect of shear forces on plate deflection. The theory also states that the approximation theory of the thin plate turns out to be invalid when the concentrated loads are large. It means that the thick plate theory must be applied by viewing the plate problem as a three-dimensional elastic problem. As a consequence, stress analysis becomes more of a role in the problem [10].

2.2 Reinforced Concrete Plates

Reinforced concrete slabs commonly used for house floors, roofs, and bridges with the following characteristics [7]:

a. Rigid
b. Able to withstand bending, either one way or two directions

c. The shear stress is relatively small unless it is subjected to a large centralized load, such as flat slab
d. Compressive reinforcement is rarely needed
e. Deflection problems are important, where the calculations are similar to beams

Based on the comparison between long and short spans, reinforced concrete slabs are distinguished from one-way and two-way slabs. The plate is said to be unidirectional when the ratio between its long and short span is twice or more. Meanwhile, it is the two-way plate if the ratio of the two is less than two. The one-way plate has only a single curvature with the main reinforcement parallel to the short side of the plate and the shrink reinforcement parallel to the long side of the plate. In two-way plates, the load is transferred to the four sides of the plate so that the main reinforcement of the plate is required on both sides of the plate [8].

2.3 Flexural Strength of Plates

By treating the one-way slab like the beam, the concrete compressive force (Cc) will be balanced by the tensile strength of the steel reinforcement (Ts) based on the balance of forces on the reinforced concrete slab section. Under reinforced conditions, the steel reinforcement has undergone melting (fc = $f\gamma$), as shown in Figure 2 below:

Cc = Ts……………………………………………………………………………… (4)
Cc = 0,85. f’c . a . b…………………………………………………………………. (5)
where a = β. C……………………………………………………………………… (6)
Ts = As . $f\gamma$……………………………………………………………………….. (7)
then the nominal moment of the cross-section is calculated by using equation 8 as follows:
Ma = Ts (d-½.a) = Cc(d-½.a) = 0,85. f’c .b. a . (d-½.a)……………………….. (8)

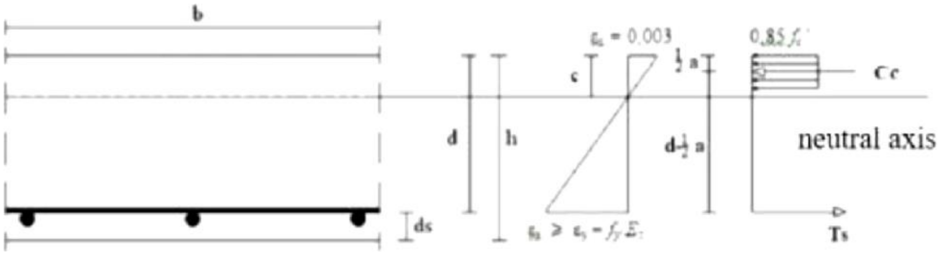

Figure 2. Solid Plate Cross-Section Stress-Strain Diagram

When there is a balance of tensile and compressive forces, the stress block on the plates is generally very small. So, theoretically, if there is a spherical cavity in the middle of the plate section, it certainly does not affect the flexural strength. It is because the compressive area is above the spherical cavity to the outermost compressive fibre. The existence of a spherical cavity aims to eliminate the concrete volumes that do not significantly affect the flexural strength of reinforced concrete plates. It means that the plate's weight becomes lighter, which results in savings of the concrete material.

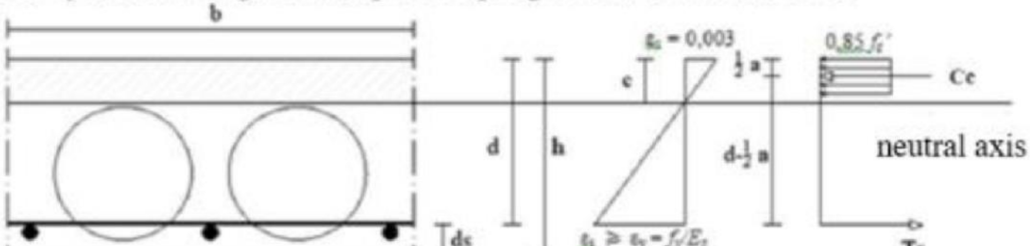

Figure 3. Spherical Hollow Plate Cross-sectional Stress Diagram

2.4. Moment Coefficient Method

The bending strength of two-way plates can be analyzed by the Moment Coefficient Method. The value of the moment in the short span direction (Mlx) and in the long span direction (Mly) is searched on the two-way plate using the moment coefficient method below:

$$M_{lx} = 0{,}001\ .\ C_x\ .\ w\ .\ L_x^2 \quad \cdots\cdots \quad (10)$$

$$M_{ly} = 0{,}001\ .\ C_y\ .\ w\ .\ L_y^2 \quad \cdots\cdots \quad (11)$$

M_{lx} = Moment of the short span direction of the plate, kNm/m’
C_x = Short span direction moment coefficient
L_x = Short span plate length, m
M_{ly} = Moment of plate length span direction, kNm/m’
C_y = Moment coefficient of long-span direction
L_y = Long span plate length, m
w = Load per square meter, kN/m^2

3. Research Methodology

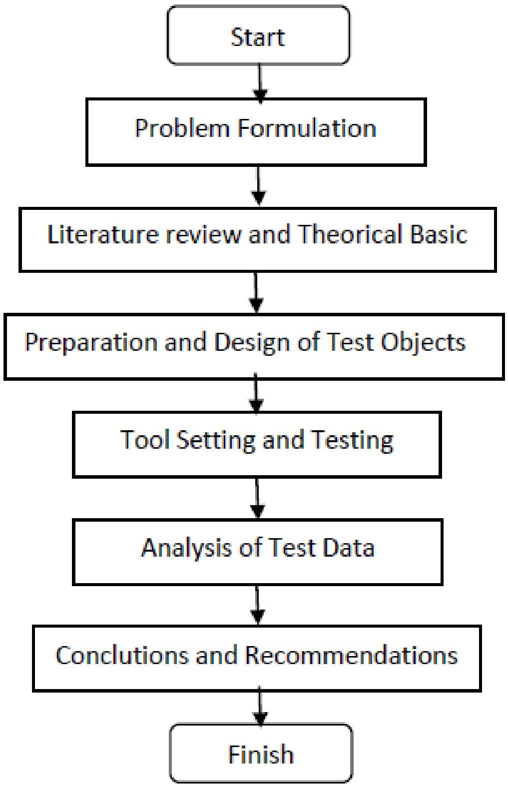

Figure 4. Research Flowchart

3.1. Test Object Details

The variable to be analyzed is a massive plate with the dimensions of 2700 mm in length, 1800 mm in width, and 140 mm in thickness (PB-1). The second plate is a PVC hollow plate with the length of

2700 mm, the width of 1800 mm, and a thickness of 140 mm (PB-2). Each cavity has been modified by using a PVC with a diameter of 760 mm and a steel diameter of 8 mm. The distance between the reinforcement is 100 mm (Figure 5).

Details of the test objects in the analysis are presented in Table 1 below.

Table 1. Design Classification of Test Objects

Plate	Plate Dimension (mm)	$\emptyset$ $Cavity$ (mm)	Distance between the balls (mm)	Dead weight per 1 m^2	ρ (%)	d (mm)	Concrete Volume
PP-1	2750x1800x140	-	-	315.663	0,403	112.4	100 %
PB-2	2750x1800x140	76	24	273.54	0,403	112.4	86.33%

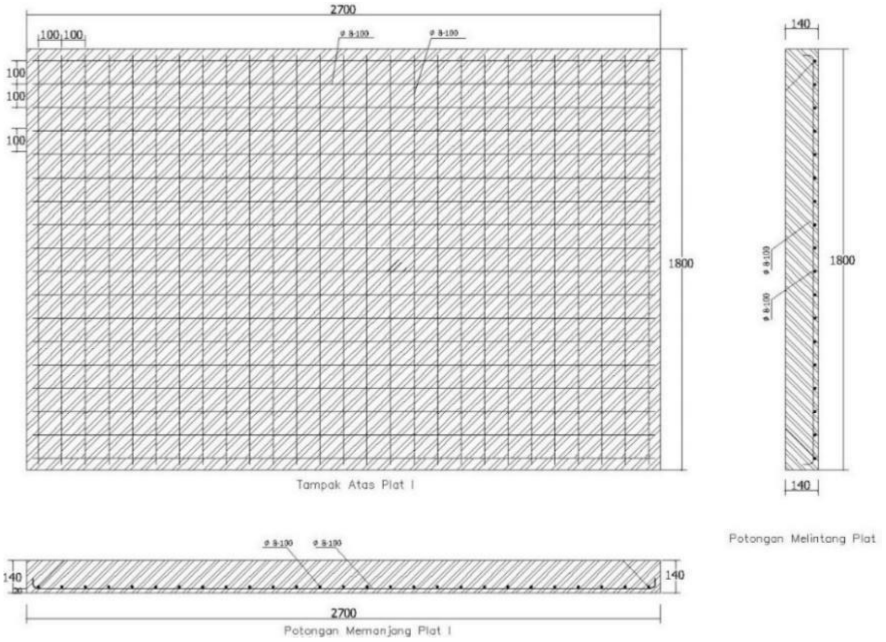

Figure 5. Solid Plate Design (PP-1)

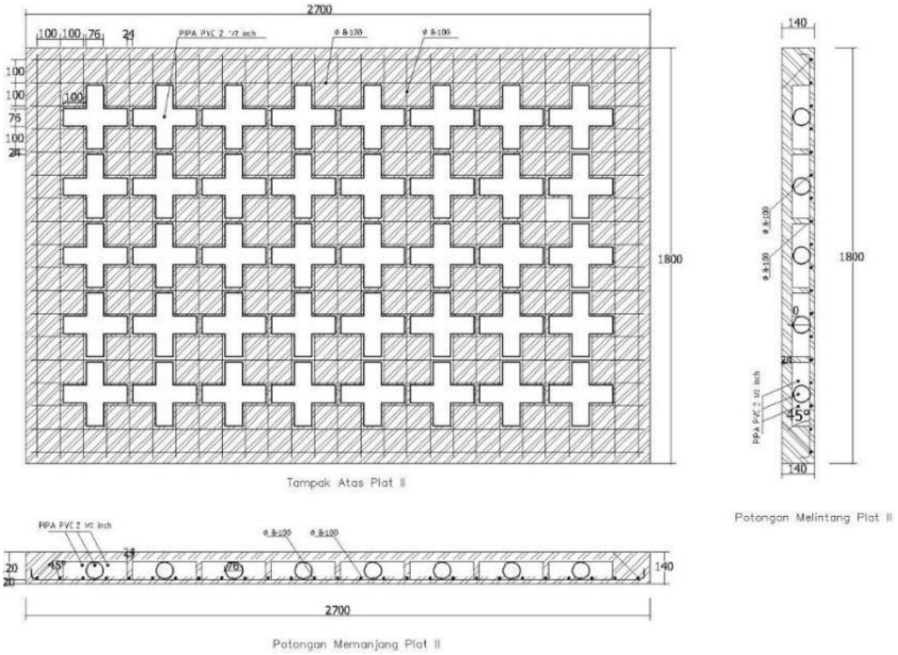

Figure 6. Hollow Plate Design (PB-2)

Figure 7. Solid Plate (PP-1) and Hollow Plate (PB-2)

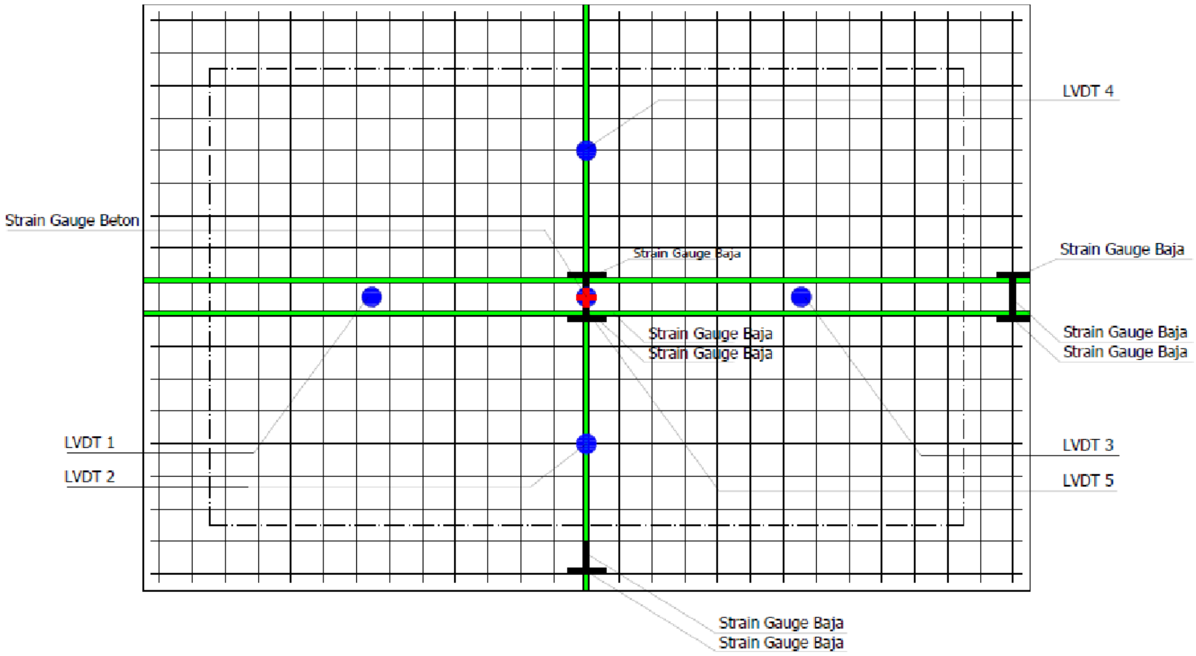

Figure 8. Placement of LVDT, Steel Strain Gauges, and Concrete Strain Gauges

The test object will be tested, at the earliest, after reaching 28 days of age. While waiting, the testing tool is set. During the test, each test object is supported by the joint supports along all four sides. The setting process of the testing tool refers to ASTM 2322, which is a two-way plate test with a uniform loading simulation.

The pattern of even loading is carried out by giving loads, in the form of sandbags, on a concrete plate, which is used to distribute the load from the hydraulic jack to the concrete plate. It is expected that the loading pattern can resemble evenly distributed loading. The loading process is carried out in stages until it reaches the expected loading capacity. The loading scheme can be seen in Figure 9 and Figure 10 below.

Figure 9. Solid Plate Loading Pattern (PP-1)

Figure 10. Hollow Plate Loading Pattern (PB-2)

4. Results and Discussion

The test result data between Solid Plate (PP-1) and Hollow Plate (PB-2) are compared. For easier reading, the data is presented in tables and histogram graphs. To make comparisons faster, the experimental data are presented in the form of a percentage. Initial crack load, melting load, and maximum load data are presented in the form of a graph of the relationship between load and deflection as shown in Figure 11.

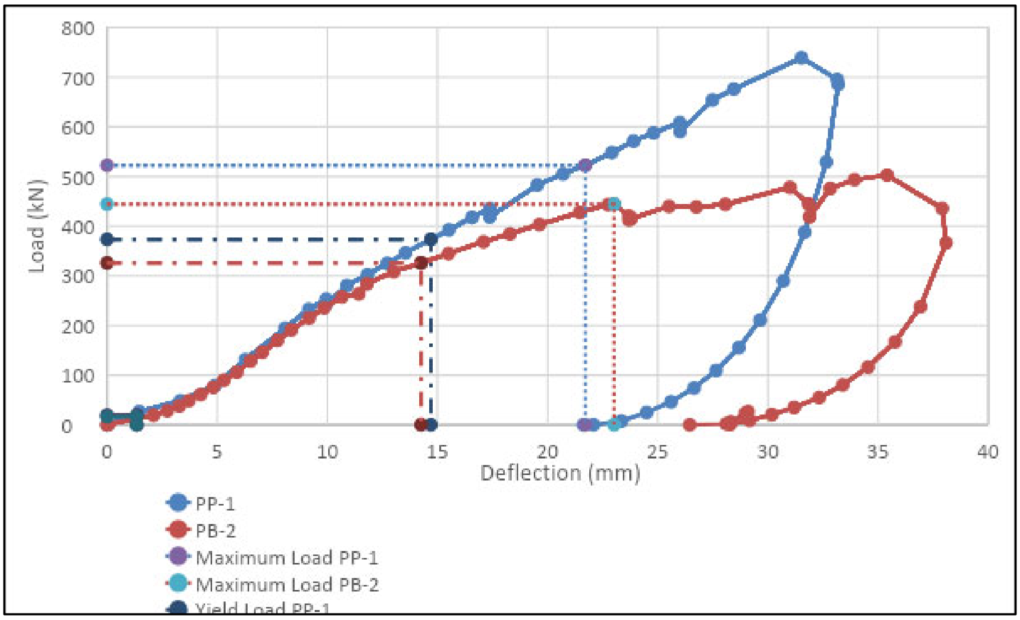

Figure 11. Relation Load and Deflection in the Middle of the Span.

Figure 11 shows the values of P_{cr}, P_y and P_{max} of each test object. For Solid Plates (PP-1), the initial P_{cr} value is 19.5 kN, with a deflection of 1.36 mm, P_y is at a load of 373.515 kN, with a deflection of 14.7 mm, and a P_{max} value of 522.66 kN, with a deflection of 21.71 mm. In the hollow plate (PB-2), the initial P_{cr} value is 16.75 kN, with a deflection of 1.34 mm, P_y is at a load of 325.935 kN, with a deflection of 14.25 mm, and a P_{max} value of 444.33 kN, with a deflection of 23.02 mm. The results above are tabulated in the form of Table 2. The results of Initial Crack Load, Yield Load and Maximum Load are below:

Table 2. Initial Crack Load, Yield Load, and Maximum Load

Plate	Crack Load (P_{cr}) (kN)	Yield Load (P_y) (kN)	Maximum Load (P_{maks}) (kN)
PP-1	19.5	373.515	522.66
PB-2	16.75	325.935	444.33
Percentage (%)	85.897	87.262	85.032

Overall, the test results show that the flexural strength of the plates has increased. However, when comparing the test results of Solid Plates (PP-1) and Hollow Plates (PB-2), at initial crack load (P_{cr}), at melting load (P_y), and maximum load (P_{max}), the load capacity of the Hollow Plate (PB-2) is lower than that of the Solid Plate (PP-1).

By loading at the initial crack load, melting load, and maximum load, the test results show that the flexural strength value of the Hollow Plate (PB-2) is smaller than that of the Solid Plate (PP-1). It happens because the compaction process of the Hollow Plate (PB-2) is less than perfect, especially at the area under the cavity. It results in the existence of porous in the tensile area, which causes cracks to occur earlier. Another cause is the concentration of tensile stress in the lower cavity area due to the three-dimensional structure of the cavity on the Hollow Plate (PB-2). It results in hollow plates being more prone to cracking compared to Solid Plates (PB-1). It shows that hollow plates (PB-2) experience flexural cracks and shear cracks.

The experimental results of loading on Solid Plates (PP-1) and Hollow Plates (PB-2) are depicted in the form of Figure 12 Histogram below.

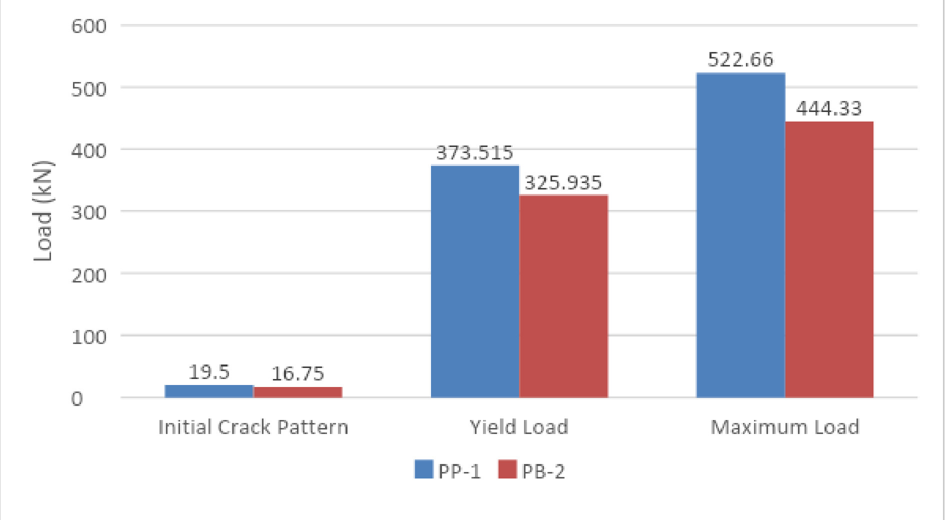

Figure 12. Comparison of PP-1 and PB-2 Loading

5. Conclusion and Recommendations

Based on the data from the research results, it can be concluded that the flexural strength of hollow concrete slabs (PB-2) is lower than that of massive slabs (PB-1). It is because the hollow plate's weight (PB-2) is reduced in the presence of PVC pipes. So it can be concluded that at maximum conditions hollow plates not only experience flexural damage but also experience sheer damage, which occurs because hollow reinforced concrete slabs (PB-2) have cavities in them. Meanwhile, hollow plates (PB-2) are more susceptible to shear cracks than massive plates (PB-1).

To obtain a more optimal comparison result and to justify any recommendations about the use of cavities in concrete slabs, it is necessary to carry out a comparative analysis by using more thickness variations, more varied concrete volumes, and other empirical approaches.

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