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Numerical Study of Flexural Performance of Reactive Powder Concrete Slabs with 15% Silica Fume and 30% Quartz Sand on Variations of Thickness and Long - Short Span Ratio

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Abstract: As the development of infrastructure progresses rapidly, concrete technology is also required to continuously improve. Numerous studies on concrete technology have been conducted to meet these demands, one of which is the innovation of Reactive Powder Concrete (RPC) with 15% silica fume and 30% quartz sand. One application of reactive powder concrete in structural element design is the concrete slab. A concrete slab is a thin structure with a horizontal plane and loads perpendicular to the plane of the structure. Concrete slabs are designed to withstand bending loads due to bending moments caused by heavy loads, which are a combination of dead loads and live loads. Therefore, it is necessary to conduct flexural performance tests on concrete slabs to determine their ability to withstand loads that cause bending moments on the slabs. The research aims to compare the experimental test results with numerical analysis of the flexural performance of reactive powder concrete slabs with varying thicknesses and span length - width ratios. The test specimens for varying thicknesses measure 70 cm x 30 cm with thickness variations of 4 cm, 5 cm, 6 cm, and 7 cm. Meanwhile, the test specimens for varying span length-to-width ratios have a thickness of 5 cm and a length of 70 cm with span length-to-width ratio variations of 2,5; 2,7; 2,9; and 3,1. The research method used is non-linear finite element analysis with ATENA Engineering Červenka Consulting software. This research includes verification of experimental test results with numerical analysis results in terms of both maximum load and maximum deflection. The verification results of numerical analysis using ATENA Engineering Červenka Consulting software with experimental testing on both thickness variations and span length - width ratio variations show a corresponding trend curve based on the load-deflection graph, with the difference in maximum load and maximum deflection values between experimental test results and numerical analysis results being below 10%.

Keywords: ATENA, Concrete Slab, Reactive Powder Concrete

Introduction

Along with the rapid development of infrastructure, the science of concrete technology is also required to continue to develop better by continuing to strive to produce concrete with high compressive strength, good performance, resistant in any condition, and environmentally friendly. Many studies on concrete technology to answer these demands, one of which is the innovation of reactive powder concrete (RPC). Reactive powder concrete is an innovative concrete technology that was originally developed by P. Richard and M. Cheyrezy in the early 1990s at the Bouyques Laboratory, Lafarge Group, France. RPC is a concrete mix with no coarse aggregate and replaces it with the use of micro-sized fine particles (Richard & Cheyrezy, 1995). The purpose of eliminating coarse aggregates is to give the concrete good homogeneity so as to produce concrete with high compressive strength and homogeneity values. The constituent components of reactive powder concrete are micro-sized particles such as cement, fine aggregate, silica fume, water, superplasticizer, and steel fibers.

Reactive powder concrete has advantages including higher compressive strength, durability, and ductility compared to conventional concrete (Sarika S & Dr. Elson John, 2015). The use of silica fume can improve the homogeneity, durability, and impermeability of concrete so that water and gas will be difficult to enter the concrete (Aisyah, 2018). Then, the addition of silica fume as much as 15% of the binder can increase the value of flexural strength in reactive powder concrete (Wibowo et al., 2022). The addition of quartz sand as much as 30% of the fine aggregate can also increase the flexural strength value of reactive powder concrete (Wibowo et al., 2024). The use of a low cement water factor (FAS) can reduce the number of pores between particles and the permeability of concrete, as well as increase the durability and strength of concrete (Alkhaly, 2017). However, this results in reactive powder concrete having low workability values (Dwiamirta & Saelan, 2022). Therefore, an alternative that can be taken to overcome this is to add a superplasticizer which functions to reduce water content and increase the workability value of concrete (Faqihuddin et al., 2021). Thus, reactive powder concrete has a high density due to the use of micro-sized materials and a low cement water factor so that this can increase the compressive strength value of concrete (Gunawan & Yahya, 2015). The use of steel fibers has the effect of increasing the value of flexural strength by 350% and compressive strength by 10% compared to reactive powder concrete without fibers (Kushartomo & Christianto, 2015).

One of the structural elements in the planning of concrete structures is concrete slabs. The emergence of reactive powder concrete as a concrete innovation that has high performance and durability and is environmentally friendly, reactive powder concrete is considered to have potential when applied as a concrete slab. Concrete slabs are thin structures with horizontal planes and loads perpendicular to the plane of the structure. Concrete slabs are planned to withstand bending loads due to bending moments caused by a heavy load, which is a combination of dead and live loads (SNI 2847, 2019). Therefore, it is necessary to test the flexural performance of the concrete slab to determine the ability of the slab to withstand loads that cause bending moments in the concrete slab.

Based on SNI 2847 2019, slabs are divided into two, namely one-way slabs and two-way slabs. One-way slabs are slabs with the ratio between the long span and the short span more than or equal to two. The concrete slab itself has a smaller thickness value compared to the span length (Syahland, 2017). Some of the things that affect minimum thickness planning include the allowable deflection rate, the quality of the material used, and the length-shortness of the size used in the planned span (Hayyu Putri et al., 2021). The strength of a floor slab as a thin structure is highly dependent on its thickness. Based on SNI 2847 2019 Article 7 the minimum required thickness for one-way slabs is L/20 for simple supports.

Based on research conducted by Fikri et al., 2023 on the effect of thickness on one-way concrete slabs concluded that the greater the thickness of the slab, the more the bending capacity increases. Khadafi (2014) conducted research by adding bendrat fiber to UHPFRC (Ultra High Performance Fiber Reinforcement Concrete) concrete slabs with variations in thickness showing that the greater the thickness of the slab, the greater the load that the slab can withstand. Research conducted by Pereira et al., (2017) on the use of bamboo material as a substitute for steel reinforcement in slabs with thickness variations on their flexural capacity resulted in the smallest deflection obtained in the slab with the largest thickness, while the largest deflection was in the slab with the smallest thickness.

To model the concrete slab in this study, ATENA (Advance Tool for Engineering Non-linear Analysis) Software was used, which is a software product based on the finite element method from Carvenka Consulting which has been established since 1992. The numerical model is the result of the discretization performed by the finite element method. Each geometry formation is an independent macroelement that is not bound to each other unless treated (Cervenka & Cervenka, 2017).

Methodology

The method used in this research is a numerical approach using the Non-Linear Finite Element Analysis (NLFEA) method using ATENA Engineering Červenka Consulting software to obtain results in accordance with the objectives of this study. After the results of this numerical analysis are obtained, it will be compared with the results of experimental testing. From the two tests, the results will be compared results in terms of ultimate load, deflection, and load-deflection curves. The reactive powdered concrete slab model used to analyze the flexural and deflection behavior has dimensions and concrete quality in accordance with the experimental tests conducted.

Experimental Sample

Detailed specifications of the specimens based on the experimental tests are shown in Table 1, Table 2, and Table 3.

Table 1. Sample Code for Compressive Strength

No	Dimension (cm)	Code	Age (Days)	Quantity
1	10 x 20	RPC-SLDR-1	28	1
2		RPC-SLDR-2	28	1
3		RPC-SLDR-3	28	1

Table 2. Code of Slab Flexure Test Piece of Thickness Variation

No	Dimension (cm)	Code	Age (Days)	Quantity
1	70 x 30 x 4	RPC-PLT-1.1	28	1
2	70 x 30 x 5	RPC-PLT-1.2	28	1
3	70 x 30 x 6	RPC-PLT-1.3	28	1
4	70 x 30 x 7	RPC-PLT-1.4	28	1

Table 3. Code of Slab Flexure Test Piece of Ly/Lx Ratio Variation

No	Dimension (cm)	Code	Age (Days)	Quantity
1	70 x 30 x 4	RPC-PLT-1.1	28	1
2	70 x 30 x 5	RPC-PLT-1.2	28	1
3	70 x 30 x 6	RPC-PLT-1.3	28	1
4	70 x 30 x 7	RPC-PLT-1.4	28	1

Experimental Testing Results

Based on the experimental test results, the compressive strength value of reactive powder concrete is 68.72 MPa. Recapitulation of RPC compressive strength test results can be seen in Table 4.

Table 4. Recapitulation of Compressive Strength Testing Results

No	Code	P (kN)	Correlation Factor	f'c (MPa)	f'cu (MPa)
1	RPC-SLDR-1	520	1,04	68,86	81,01
2	RPC-SLDR-2	515	1,04	68,19	80,22
3	RPC-SLDR-3	522	1,04	69,12	80,14
Average				68,72	80,85

A recapitulation of the results of flexural testing of reactive powder concrete slabs with varying thickness can be seen in Table 5.

Table 5. Recapitulation of Slabs Flexure Testing Results of Thickness Variations

No	Code	P (N)	Δ (mm)
1	RPC-PLT-1.1	6474,60	0.460
2	RPC-PLT-1.2	9414,38	0.360
3	RPC-PLT-1.3	12748,65	0.290
4	RPC-PLT-1.4	14420,70	0.192

A recapitulation of the results of flexural testing of reactive powder concrete slabs with variations in the long - short span ratio (Ly/Lx) can be seen in Table 6.

Table 6. Recapitulation of Slabs Flexure Testing Results of Ly/Lx Ratio Variations

No	Code	P (N)	Δ (mm)
1	RPC-PLT-1.1	6474,60	0.460
2	RPC-PLT-1.2	9414,38	0.360
3	RPC-PLT-1.3	12748,65	0.290
4	RPC-PLT-1.4	14420,70	0.192

Modeling in ATENA Engineering Červenka Consulting Software

1. Define the material properties of the reactive powder concrete as well as the steel plate as the support. The reactive powder concrete is defined as 3D Non-Linear Cementitious 2 with a cube characteristic compressive strength (f'cu) of 80.85 MPa, elastic modulus (E) of 38948.05 MPa, and tensile strength (fct) of 4.63 MPa. The material properties of reactive powder concrete can be seen in Figure 1. Then the steel plate is defined as 3D Elastic Isotropic where the steel plate behaves as an elastic material with unlimited strength which is used as the base material receiving the load directly and as the support of the plate. The material properties of the steel plate can be seen in Figure 2.

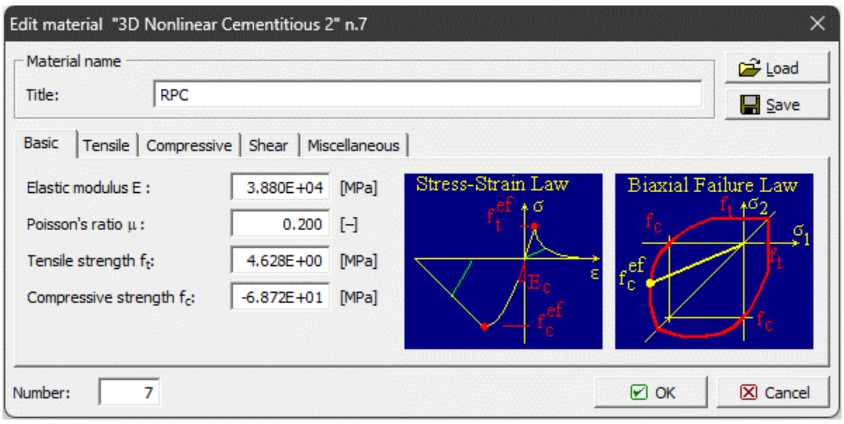

Figure 1. Material properties of Reactive Powder Concrete

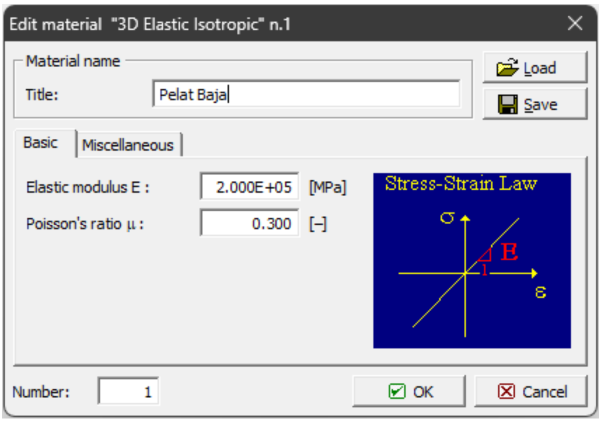

Figure 2. Material properties of steel plates

2. Modeling a concrete slab with the shape and dimensions according to experimental testing with joint placement located at each corner of the slab model and at each support location and centralized load for the application of boundary condition placement. The topology of the reactive powder concrete slab can be seen in Figure 3.

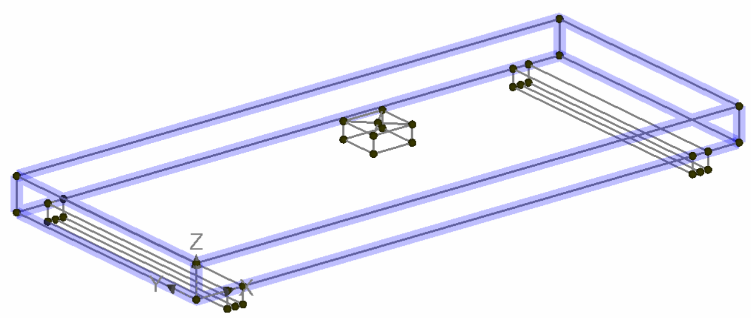

Figure 3. RPC Slab topology (RPC-PLT-1.1)

3. The load and support are placed according to the experimental tests. The load case used is force to define the load, and support to define the support. A single point loading at the top center of the RPC slab span 300 mm away from the fulcrum was applied with a loading rate of 20 kgf (1.961 x 10-4 MN) at each step. Every 20 kgf loading, the deflection that occurs in the RPC slab will be calculated and shown in the final result in the form of a load-deflection graph. The load and support of the reactive powder concrete slab can be seen in Figure 4.

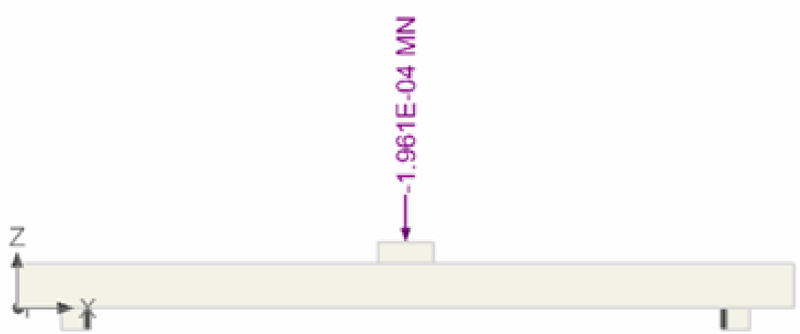

Figure 4. Load and support of RPC slab (RPC-PLT-1.1)

4. Performing meshing using the mesh type applied is brick with an element size of 0.02m. The meshing of the reactive powder concrete slab can be seen in Figure 5.

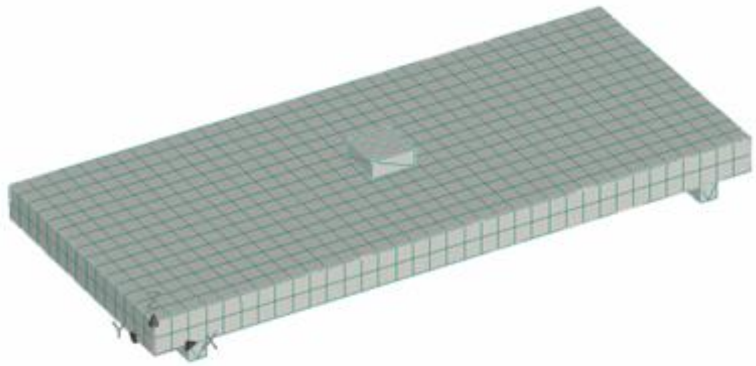

Figure 5. RPC slab meshing (RPC-PLT-1.1)

5. Defining analysis steps. In the load case, the load is defined as a combination of loads in an attempt to formulate a loading history so that the loading can be increased until collapse of the structure occurs. Before running the program the maximum load is estimated according to the experimental tests.
6. Determining monitoring points. In determining the load-deflection curve, two monitoring points are required to be placed at the same location as the experimental team, namely the first point at the bottom center of the slab span, to monitor the deflection of the slab and the second point at the loading point, which is to determine the ultimate load value located above the steel plate at the top center of the slab where the load is applied. The monitoring points of the reactive powder concrete slab can be seen in Figure 6.

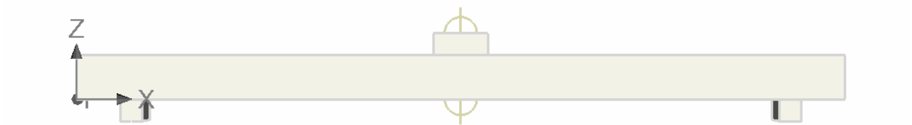

Figure 6. RPC slab monitoring points (RPC-PLT-1.1)

Result and Discussion

The results of numerical analysis using ATENA software that have been obtained are then verified with experimental test results. The data results are processed and displayed in the form of load-deflection graphs as follows.

Thickness Variations

The load-deflection graph of the comparison between the experimental test results and the results of numerical analysis using ATENA software on thickness variations can be seen in Figure 7 for a thickness of 4 cm, Figure 8 for a thickness of 5 cm, Figure 9 for a thickness of 6 cm, and Figure 10 for a thickness of 7 cm.

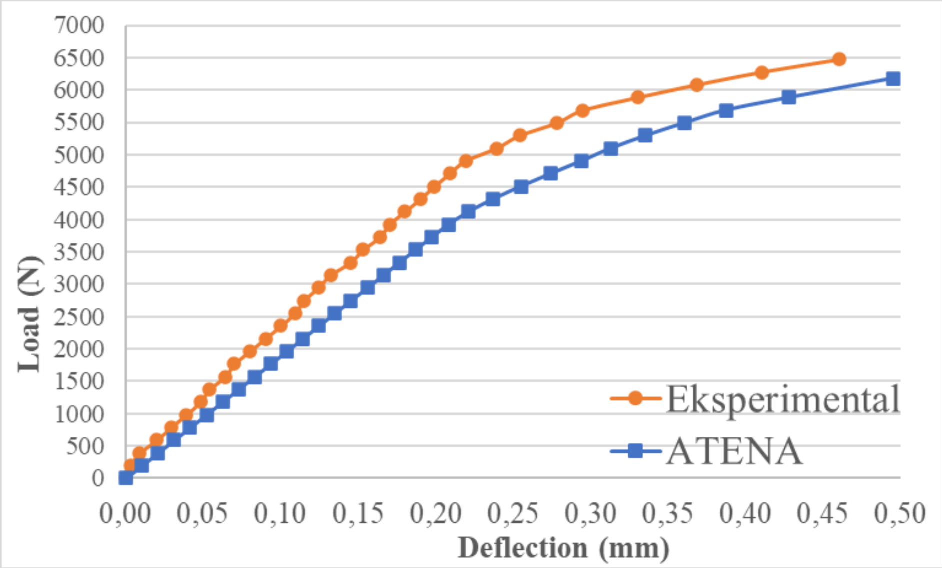

Figure 7. Load deflection graph of 4 cm thick slab

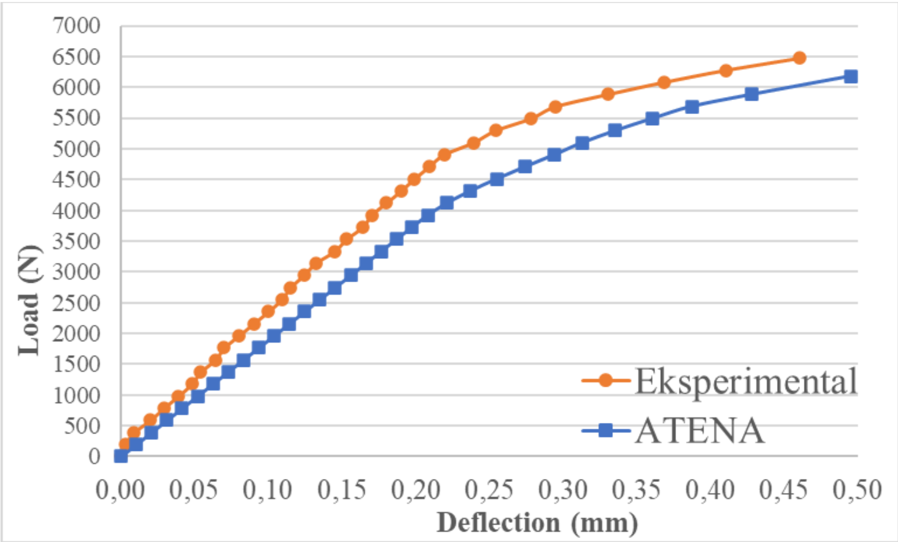

Figure 8. Load deflection graph of 5 cm thick slab

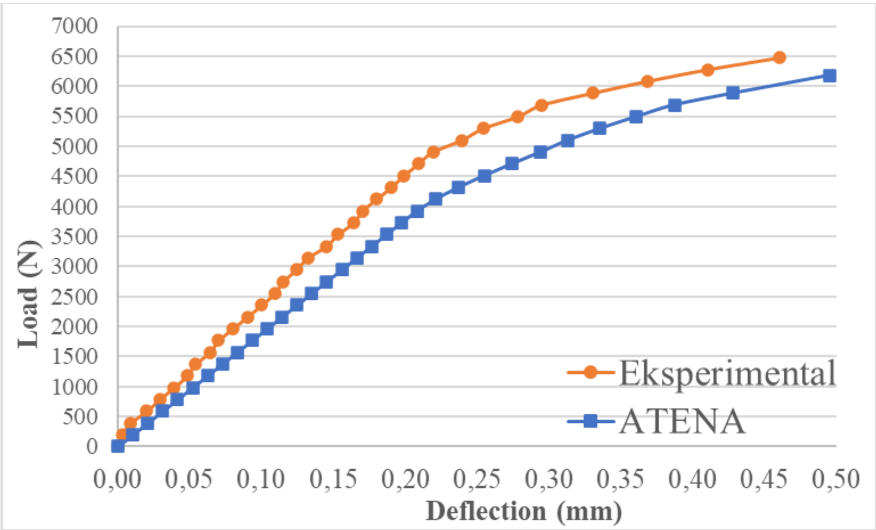

Figure 9. Load deflection graph of 6 cm thick slab

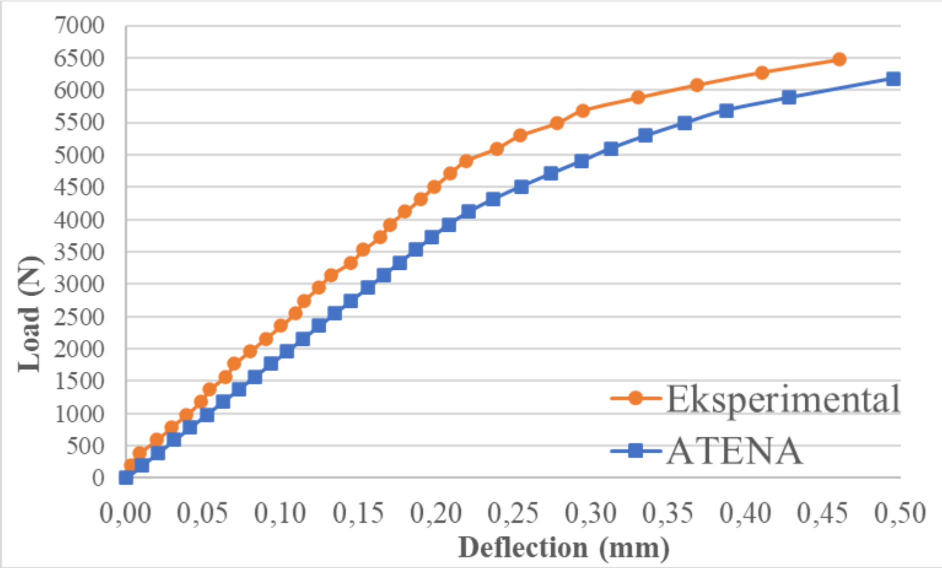

Figure 10. Load deflection graph of 7 cm thick slab

A recapitulation of the comparison of experimental test results with the results of ATENA numerical analysis of reactive powder concrete slabs with thickness variations can be seen in Table 7.

Table 7. An example of a table (font size 10pt)

Specimen	Ultimate Load			Deflection		
	Eksperimental (N)	**ATENA (N)**	**Error (%)**	**Eksperimental (mm)**	**ATENA (mm)**	**Error (%)**
RPC-PLT-1.1	6474,60	6179,00	4,566	0,460	0,495	7,565
RPC-PLT-1.2	9417,60	8924,00	5,241	0,360	0,390	8,333
RPC-PLT-1.3	12753,00	12160,00	4,650	0,290	0,315	8,517
RPC-PLT-1.4	14420,70	14370,00	0,352	0,192	0,193	0,469

Long - Short Span Ratio (Ly/Lx) Variations

The load-deflection graph of the comparison between the experimental test results and the results of numerical analysis using ATENA software on long - short span ratio (Ly/Lx) variations can be seen in Figure 11 for Ly/Lx 2,5; Figure 12 for Ly/Lx 2,7; Figure 13 for Ly/Lx 2,9; and Figure 14 for Ly/Lx 3,1.

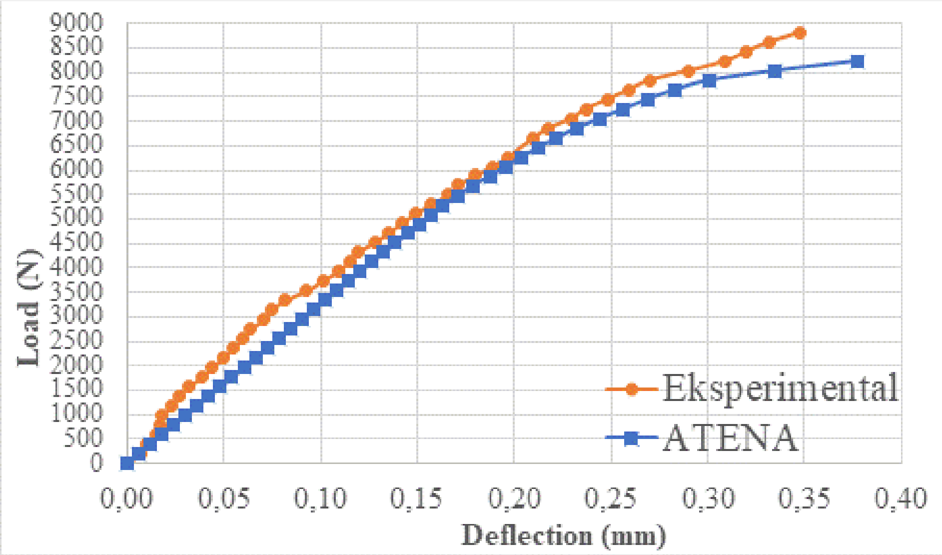

Figure 11. Load deflection graph of Ly/Lx 2,5 slab

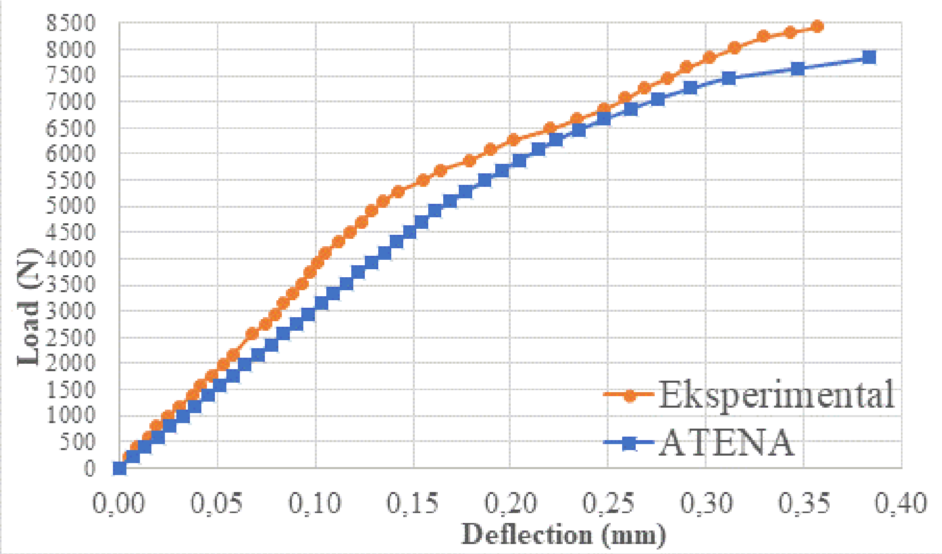

Figure 12. Load deflection graph of Ly/Lx 2,7 slab

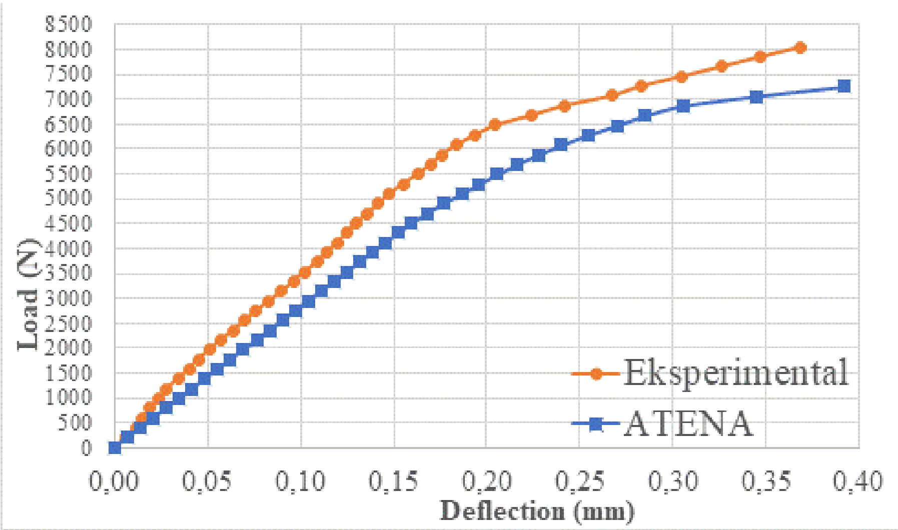

Figure 13. Load deflection graph of Ly/Lx 2,9 slab

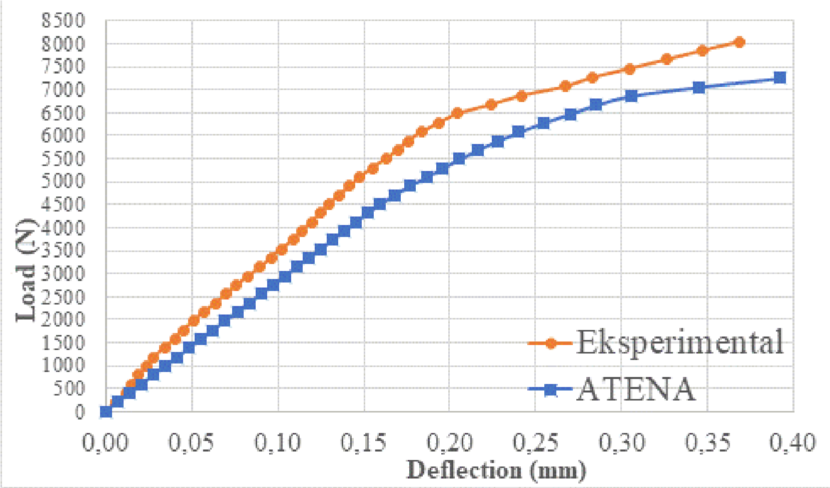

Figure 14. Load deflection graph of Ly/Lx 3,1 slab

A recapitulation of the comparison of experimental test results with the results of ATENA numerical analysis of reactive powder concrete slabs with long - short span ratio (Ly/Lx) variations can be seen in Table 8.

Table 8. An example of a table (font size 10pt)

Specimen	Ultimate Load			Deflection		
	Eksperimental (N)	**ATENA (N)**	**Error (%)**	**Eksperimenta l (mm)**	**ATENA (mm)**	**Error (%)**
RPC-PLT-2.1	8829,00	8236,00	6,717	0,348	0,377	8,333
RPC-PLT-2.2	8436,60	7844,00	7,024	0,357	0,384	7,507
RPC-PLT-2.3	8044,20	7552,00	6,119	0,369	0,392	6,314
RPC-PLT-2.4	7455,60	6963,00	6,607	0,375	0,401	6,933

Conclusion

The verification results of numerical analysis using ATENA Engineering Červenka Consulting software with experimental testing on thickness variations show the same curve trend based on the load-deflection graph. This is evidenced by the difference in ultimate load and deflection values between experimental test results and numerical analysis below 10%.

The verification results of numerical analysis using ATENA Engineering Červenka Consulting software with experimental testing on the variation of the long - short span ratio (Ly/Lx) show the same curve trend based on the load-deflection graph. This is evidenced by the difference in the ultimate load and deflection values between the experimental test results and the numerical analysis results below 10%.

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