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The Ultrasonic Pulse Velocity and Lagrangian Approaches to Predict the Effective Thickness and Homogeneity of the Sandwich Panel

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ABSTRACT

Non-destructive testing can be applied to various things, including sandwich panels. Sandwich panels made of EPS are greatly affected by the mixing process. Bad mixing can affect the level of homogeneity and reduce quality. In addition, the improper thickness of layers and cores can result in wall damage. For this reason, carrying out a non-destructive test on the sandwich panel is necessary. This study aims to determine the homogeneity of the material and predict the dimensions of the EPS core and layer. Experimental testing was conducted using Ultrasonic Pulse Velocity (direct method) with 90 points. The test object consisted of six sandwich panel walls with three variants, each with dimensions and layer thickness of 15 mm, 20 mm, and 25 mm, respectively, while the core layer size was 70 mm, 80 mm, and 90 mm, respectively. The test results were analyzed on travel time and wave velocity using a statistical analysis approach including covariance, Kolmogorov-Smirnov, ANOVA, t-test, and Lagrangian. The analysis results show that the mixture's homogeneity can be determined based on the ultrasonic pulse velocity. The proposed Lagrange analysis can reveal the behavior of the propagation speed. Based on the results of the Lagrange approach, the highest speed is obtained at a thickness of 80 with a maximum speed of 2.395 km/s. The results of this study contribute to the non-destructive test procedure, especially in determining homogeneity and the dimensions of the effective thickness of the structural walls (cores and layers) that have been installed in the field quickly, cheaply, accurately, and briefly.

1. Introduction

Lightweight concrete uses lightweight aggregates with a specific gravity ranging from 600-1600kg/m3 [1]. Using lightweight materials can reduce the structure's weight, which

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impacts lateral force reduction, especially in earthquakes. Two types of lightweight aggregates are natural (pumice, volcanic ash) and artificial. One of the artificial lightweight aggregates is EPS (expanded polystyrene) [2]. EPS is the most widely used material because it is extremely light [2]. The EPS cutting method in powder form is assumed to replace the fine aggregate in the sandwich wall mixture. EPS is necessary because this material cannot be decomposed and can even become microplastics that can pollute the environment [3].

Furthermore, EPS also has advantages, including that it does not contain chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs) [2] [4], has mechanical properties that can insulate thermals and can be made in such a way that it is easy to use as a composite mixing material on wall panels or floors. EPS has characteristic properties, including good heat conductivity, sound damping, and water absorption. Therefore, it is believed to be an alternative for developing environmentally friendly materials with a percentage greater than fifty percent of the volume of sandwich panel walls.

Presently, the type of EPS testing includes material modification in concrete and mechanical characteristics related to mechanical, chemical, or thermal [2]. Babu et al. [4] propose a combination of EPS and fly ash additives with compositions of 0% up to 66.5% and 50%, respectively, with varying densities between 0.550 g/cm^3 up to 2,200 with compressive strength ranges varying from 0.55MPa to 22MPa. Another researcher, Tabatabaiefar [5], analyzed the distribution of stresses in sandwich panels on flexural loading, the effect of moisture content on the mechanical properties of the panels, and revealed the creep load.

Priya and Sivakumar [6] analyze the material property of EPS as a bearing wall. The focus of the study refers to the mechanical properties (compressive strength and flexural strength) and thermal conductivity due to the role of EPS in the wall mixture. Variations in using EPS are determined in the range of 0% to 100% with an interval of 20. The test results recommend that using EPS at 60% of the wall volume will reduce structural weight and thermal well. Meanwhile, Matsuo [7] reported the other side of the mechanical properties of EPS walls besides compressive strength, namely resistance to infrared radiation. Research continues to be developed towards the use of steel composite materials [8], microstructural investigations with other additives [9], stress and strain behavior, combination with bricks [10], FEM modeling between EPS and concrete block [11], and feasibility studies [12]. The flexural strength test performance was also developed to obtain optimal results regarding the lightweight behavior of foam concrete sandwich panels under axial load. [13], the utilization composite concrete filled circular steel tubes [14], mixed compositions for high-strength concrete using polystyrene

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beads [15], recommendations for the use of hybrid foamed concrete sandwich panel technology for the precast concrete industry [16], modification of sandwich panel with double shear truss connectors to increase the flexural performance [17], laboratory scale precast concrete sandwich panel for flexural loading test [18], the resistance of lightweight panel during exposed to flame [19], and The new technique expanded polystyrene as an aggregate to prevent segregation during the material mixing process and loss of weight [20].

Although extensive research and modifications have been carried out on EPS, the main problems of lightweight composite materials related to homogeneity and prediction of the most effective thickness have not been discussed. This is important to demonstrate because sandwich walls made of EPS are significantly affected by the mixing process, which can affect quality. It is important to determine the most effective thickness because inappropriate layer thickness can result in rapid wall damage. Therefore, one of the proposed methods to measure material homogeneity is ultrasonic pulse velocity (UPV). The direct method is rightly implemented because it has a relatively high level of accuracy compared to indirect and semi-direct [21][22]. The level of accuracy of readings is influenced by several factors, including the influence of aggregate dimensions, density, voids in structural components, material homogeneity, transducer distance (transmitter to receiver), and the consistency of the coupling agent as a medium to facilitate the distribution of ultrasonic signals or waves. Surface leveling and initial calibration must be carried out to obtain the material's specific characteristics to minimize interference due to readings.

Based on the initial findings, the test results show instability due to the influence of thickness, core, and layers. The difficulty increases with reading errors because the waves are not in direct contact (transmitter to receiver). As an initial assumption, the waves are predicted not to radiate straight, but there is a bias due to the use of seventy percent polystyrene. Analysis with an ultrasonic pulse velocity approach aims to determine the homogeneity, covariance, and effect of core and layer thickness on velocity. In contrast, the mathematical approach (Lagrange) aims to find new information about the effectiveness of reading and predicting the thickness of the core layer and an adequate layer to strengthen the experimental test results.

This study aims to determine the homogeneity of the material and predict the dimensions of the Expanded Polystyrene (EPS) core and layer. A direct test scheme is applied to obtain the travel time of the data distribution from ninety test points. The reliability of the test was checked through several stages, including the covariance test, homogeneity, Kolmogorov-Smirnov test, and t-test. The results obtained from the analysis are pulse velocity, which will be used as the basis for determining material quality decisions and predicting the

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dimensions of the core wall and layer. Therefore, this research contributes to the non-destructive test procedure, especially in determining homogeneity and the dimensions of the effective thickness of the structural walls (cores and layers) that have been installed in the field quickly, cheaply, accurately, and briefly.

2. Research Method

This study uses an experimental method with quantitative descriptive data analysis. The research was conducted at the structure and materials laboratory, Faculty of Engineering, Universitas Negeri Yogyakarta. The research phases start from (1) trial mix; (2) the milling process into polystyrene granules; (3) the manufacture of the specimen; (4) Ultrasonic pulse velocity testing; (5) statistical test, and (5) the Lagrangian test. In this study, samples were used with notations SP_{70}, SP_{80}, and SP_{90}. The mixed proportions for each specimen and the specimens on the sandwich panel are shown in **Table 1.** and **2.**

Table 1. Mix Proportion For Each Specimen

Materials	SP_{70} (kg)	SP_{80} (kg)	SP_{90} (kg)
Styrofoam	0.575	0.655	18.140
PPC	14.110	16.125	22.585
Fine aggregate	17.565	20.075	10.365
water	8.065	9.215	0.740

Source: Research Proportion Analysis (2022)

Tabel 2. Specimen sandwich panels (SP)

Notation	Core (mm)	Layer (mm)	Point
SP_{70A}	70	25	15
SP_{70B}	70	25	15
SP_{80A}	80	20	15
SP_{80B}	80	20	15
SP_{90A}	90	15	15
SP_{90B}	90	15	15
	Total		90

Source : Research Data (2022)

Table 1 illustrates that each material has a different proportion in each sample. In contrast, **Table 2** shows that SP70 A and B are sandwich panels with dimensions of 70 mm core and 25 mm layer, SP80 A and B are 80 mm core and 20 mm layer, and SP90 A and B are 90 mm core and 15 mm layer. Direct testing was carried out on fifteen test points, with a

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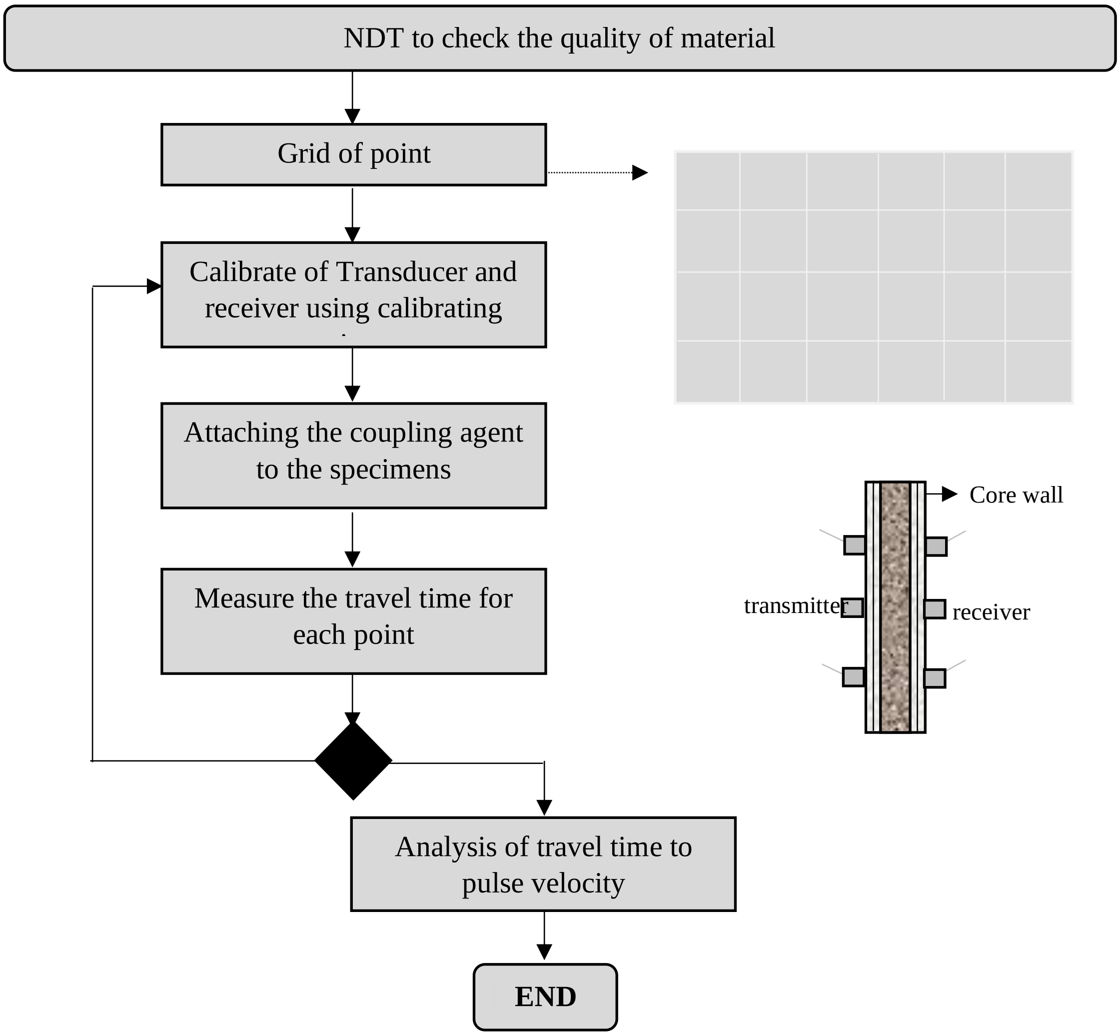
transducer distance of 100 mm. The representation of the value of the test results above is travel time, which is then converted into speed. Furthermore, the speed will be influenced by the length of the media. In this case, there are two variables: the core and the layer.



Source : Research Procedure for NDT test (2022)

Figure 1. Test Methodology

Figure 1 describes the test method on a sandwich panel specimen. The test object draws a grid system with a distance of 100 mm in the vertical and horizontal directions. Afterward, the UPV (transmitter and receiver) are calibrated using a proof ring according to the material of the test object. The testing process coats the coupling agent on the transmitter and receiver with a consistent thickness (1 mm up to 2 mm). The digital number will report the wave reading result (travel time). The travel time test calculated speed values to be analyzed using statistical tests related to covariance (to determine the allowable deviation), Kolmogorov-Smirnov (homogeneous sample), ANOVA test, t-test, and Lagrangian test based on pulse velocity.

2.1 UPV Methods

The method used in this test uses a direct approach, with the test formation in Figure 2. In contrast, the ultrasonic pulse velocity test refers to [23]. Based on European standards EN 12504-4, BS EN 12504-4 [24], two transmission methods (transducer and receiver) is applied with a frequency transmission system of 54kHz. UPV testing methods are divided into three: (1) direct, (2) indirect, and (3) semi-direct testing. Based on the three methods, direct is the best alternative because it has a good level of accuracy [21] [22]. The value of the pulse velocity is calculated by Equation.

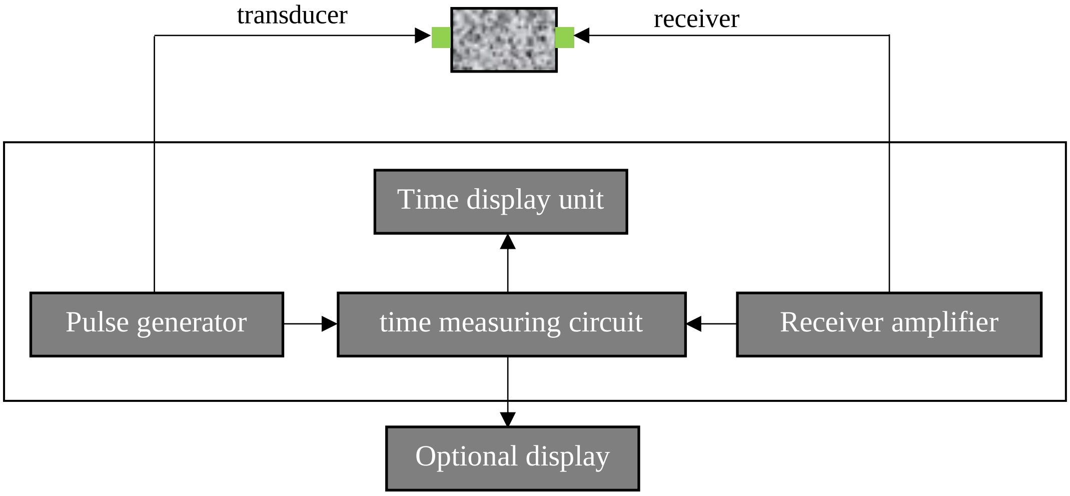
$$V = \frac{L}{T}$$

With:

V = Velocity (km/s)

L = Length (km)

T = Travel time (s)



Source: Experimental Work on UPV (2022)

Figure 2. The Mechanism of the UPV Test

Ultrasonic pulse velocity test results are travel time (TT). This value will be converted using equation. According to [21] [22], the magnitude of the speed value is based on the level of distance traveled, (2) the object or specimen, (3) the voids in the mixture, (4) homogeneity, (5) the testing method applied (direct, indirect, semi-direct), and (6) the viscosity of coupling agents.

2.2 Statistic test and Lagrangian

Statistical testing consists of covariance, Kolmogorov-Smirnov, ANOVA, and the t-test. The covariance test aims to find the deviation of the test data with acceptance criteria of

10 percent. While the Kolmogorov-Smirnov test was carried out to determine homogeneous tests, the ANOVA was for data normality, and a t-test was carried out to determine the effect of core and layer thickness on the UPV test. In particular, a Lagrangian analysis was performed to support the UPV test and analyze an optimization function for the velocity at each stage of the direct test. Therefore, the presence of EPS-interfering media will be transformed into a function without constraints, and the concern of thickness prediction can be decrypted.

3. Results and Discussions

3.1 Pulse Velocity

The result of the ultrasonic test is the travel time. These values are analyzed to produce the wave propagation (pulse velocity), the analysis results are presented in **Table 3**.

Table 3. Analysis of Pulse Velocity

Notation	Point (average)	V (km/s)	Notation	Point (average)	V (km/s)
$SP70_A$	P_1	1.608	$SP70_B$	P_1	1.608
	P_2	1.798		P_2	1.697
	P_3	1.656		P_3	1.506
	P_4	1.644		P_4	1.512
	P_5	1.541		P_5	1.477
$SP\ 80_A$	P_1	2.018	$SP80_B$	P_1	2.147
	P_2	1.900		P_2	2.217
	P_3	1.866		P_3	2.137
	P_4	1.969		P_4	2.076
	P_5	1.903		P_5	1.945
$SP90_A$	P_1	1.799	$SP90_B$	P_1	2.153
	P_2	1.854		P_2	2.191
	P_3	1.803		P_3	2.317
	P_4	1.847		P_4	2.260
	P_5	1.791		P_5	2.133

Source: Research Analysis (2022)

In this study, velocity is a representation of density and homogeneity. Based on **Table 3**, $SP70_{A,B}$ $SP80_{A,B}$ and $SP90_{A,B}$ the average are 1.065 km/s, 2.018 km/s, and 2.015 km/s, respectively. Pulse velocity decreases using 70 mm and 25 mm thick core and layer layers. The wave speed will be high if it passes through solid media [23]. However, based on the test with a larger layer thickness on the $SP70_{A,B}$ specimen compared to other test objects, there is a disturbance in the speed of propagation which means that there is a variety of wave refraction patterns. This can be caused by the density of the test object and wave refraction due to the influence of Styrofoam (EPS) material.

In the exact mechanism, increasing the core dimensions to 80 mm and 90 mm can increase the speed by 25.74% and 25.55%, respectively. This indicates that the core dimensions

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significantly affect the ultrasonic wave propagation speed value. Attempts to thicken the layers will refract the waves and reduce the velocity value, depending on the predetermined compressive strength. Therefore, several possible causes for the decreasing velocity value include the layer mass density, which has a linear effect on the strength of the material.

Efforts to increase the core thickness do not change the quality of the wave propagation speed. The decrease in velocity indicates that the optimal values are obtained for the core dimensions and layer thicknesses of 80 mm and 20 mm. This value is an interesting parameter in this study, which is proposed to use mortar layer thickness in construction projects, especially in lightweight composite wall materials. Although SNI 2847-2019 [1] requires an optimum thickness of 15 mm, this does not apply to lightweight concrete combined with conventional mortar.

3.2 Material Homogeneity

The material mixing process has a higher level of difficulty compared to conventional concrete. Adding styrofoam by 70 % of the volume of the mixture results in a loss of mixing mass (especially styrofoam). The stirring strategy is carried out by processing between water and styrofoam first, then adding to the dry mix using a special tool to achieve a good level of homogeneity.

Furthermore, the normality test of the data with ANOVA analysis was carried out to determine the level of the normal distribution with a significance level of 5%, as proposed by [21]. It is necessary because the assumption of the material forming the specimen consists of various characteristics (fine aggregate, water, polystyrene), and it is necessary to accomplish a homogeneity test [21].

Table 4. Analysis of Covariance

Specimen	Point (average)	V (km/s)	COV (%)	specimen	V (km/s)	COV (%)
$SP70_A$	P_1	1.608	5.721	$SSC70_B$	1.608	5.838
	P_2	1.798			1.697	
	P_3	1.656			1.506	
	P_4	1.644			1.512	
	P_5	1.541			1.477	
$SP80_A$	P_1	2.018	3.169	$SSC80_B$	2.147	4.856
	P_2	1.900			2.217	
	P_3	1.866			2.137	
	P_4	1.969			2.076	
	P_5	1.903			1.945	
$SP90_A$	P_1	1.799	1.614	$SSC90_B$	2.153	3.466
	P_2	1.854			2.191	
	P_3	1.803			2.317	
	P_4	1.847			2.260	
	P_5	1.791			2.133	

Source: Author's analysis (2022)

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The results in **Table 4** show a good level of test variation with average scores below 10 % based on the significance level. This shows that the method of carrying out the work of mixing sandwich panel walls is acceptable (homogeneous). Furthermore, the analysis was carried out using the Kolmogorov-Smirnov method to determine the data distribution with a normal distribution.

Table 5. Analysis of Kolmogorov-Smirnov

Specimen	Analysis	Results
$SP70_{A,B}$	$0.875 < X < 0.818$	normal
$SP80_{A,B}$	$0.722 < X < 0.941$	normal
$SP90_{A,B}$	$0.828 < X < 0.845$	normal

Source : Author's Analysis (2022)

Table 5 is used for the next step using parametric analysis (ANOVA and t-test) to find the value of material homogeneity. It means that the Kolmogorov-Smirnov results can be continued for analysis because if the significance of the data to be tested has a significant difference from standard normal data, it means that the data is normal.

3.3 Statistic Test

The results of the Kolmogorov-Smirnov test showed that the data were normally distributed. In contrast, the results of the ANOVA analysis showed a value of $0.011 < 0.05$, which means that the mixing material is homogeneous. Therefore, the test results are continued by analyzing the effect of core thickness on wave propagation speed. Two-tail t-test analysis was carried out with $0.026 < 0.05$, which means that there is a significant effect due to differences in the thickness of the core and wall layers.

3.4 Lagrangian Approach

Lagrange analysis can be used to predict paired data in various applications, such as particulate two-phase flow [25], discrete particle behavior prediction [26], and coupled program finite element method [27]. In principle, if the data pair $(x_i, y_i),\ 0 \leq i \leq n$ is available, then the Lagrange interpolation $L_n(x)$ is an interpolation in the form of an n-order polynomial such that $L_n(x_i) = y_i$ *for* $i = 0, 1, 2,..n$. At point x, which is not the observation point, the Lagrange value can be calculated using the formula:

$$L_n(x) = \sum_{i=0}^{n} P_{ni}(x)\, y_i$$

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With

$$P_{ni}(x) = \prod_{i=0, i\neq k}^{n} \left(\frac{x - x_i}{x_k - x_i}\right).$$

Based on the experiment for a thickness of 70 mm, data is obtained as shown in **Table 6**.

Table 6. Analysis method for t = 70 mm

n	**0**	**1**	**2**	**3**	**4**
x_i	100	200	300	400	500
y_i	1.531	1.582	1.564	1.431	1.392

Obtained:

$$P_{4100}=\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{(100\text{-}200)(100\text{-}300)(100\text{-}400)(100\text{-}500)}$$

$$=\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{2400000000},$$

$$P_{4200}=\frac{(x\text{-}100)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{(200\text{-}100)(200\text{-}300)(200\text{-}400)(200\text{-}500)}$$

$$=-\frac{(x\text{-}100)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{600000000},$$

$$P_{4300}=\frac{(x\text{-}100)(x\text{-}200)(x\text{-}400)(x\text{-}500)}{(300\text{-}100)(300\text{-}200)(300\text{-}400)(300\text{-}500)}$$

$$=\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{400000000},$$

$$P_{4400}=\frac{(x\text{-}100)(x\text{-}200)(x\text{-}300)(x\text{-}500)}{(400\text{-}100)(400\text{-}200)(400\text{-}300)(400\text{-}500)}$$

$$=-\frac{(x\text{-}100)(x\text{-}200)(x\text{-}300)(x\text{-}500)}{600000000},$$

$$P_{4500}=\frac{(x\text{-}100)(x\text{-}200)(x\text{-}300)(x\text{-}400)}{(500\text{-}100)(500\text{-}200)(500\text{-}300)(500\text{-}400)}$$

$$=\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{2400000000}$$

Lagrange polynomial:

$$L_4(x)=1.531\,\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{2400000000}$$

$$-1.582\,\frac{(x\text{-}100)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{600000000}$$

$$+1.564\,\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{400000000}$$

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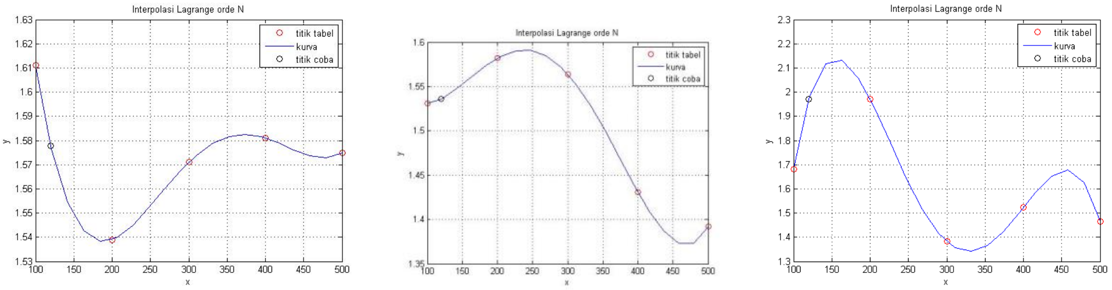
$$-1.431\frac{(x\text{-}100)(x\text{-}200)(x\text{-}300)(x\text{-}500)}{600000000}$$

$$+1.392\frac{(x\text{-}200)(x\text{-}300)(x\text{-}400)(x\text{-}500)}{2400000000}$$

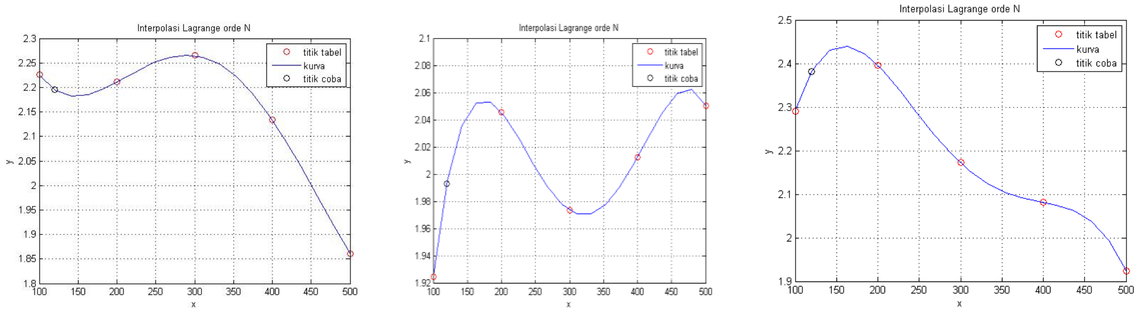
Based on the simulation for a thickness of 70 mm, the maximum pulse velocity is 1.971 km/s.



Source: Author's analysis (2022)

Figure 3. Pulse velocity for t =70mm

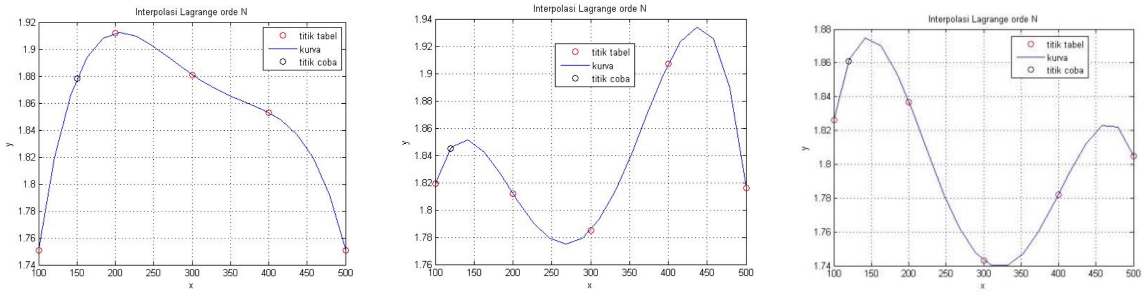
Furthermore, the maximum velocity for a thickness of 80 mm is 2.395 km/s, as shown in **Figure 4.**



Source: Author's analysis (2022)

Figure 4. Pulse velocity for t =80mm

For the thickness of 90 mm, the maximum speed is 1.912km/s as shown in **Figure 5**.



Source: Author's analysis (2022)

Figure 5. Pulse velocity for t = 90mm

Figures 3 to **5** show that the highest pulse velocity is 2,395 km/s at a core thickness of 80 mm. The optimal thickness cannot be judged based on the size of the core or layer dimensions. However, in the results of the Lagrangian analysis, an optimal value was found which tends to be in line with the results of the t-test analysis.

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The Lagrangian approach emphasizes optimization problems that cannot be solved due to constraints that limit the objective function. Lagrange's characteristic approach is being able to transform the optimization problem due to the influence of two variables into an optimization problem without constraints. Therefore, the optimization problem can be solved as indicated by the effective core and layer thickness of 80 mm and 20 mm, respectively.

4. Conclusion

The analysis results show that the homogeneity of the mixture can be determined based on the ultrasonic pulse velocity, which is proven by ANOVA analysis with $0.011 < 0.05$. Meanwhile, the results of the t-test report that there is a significant effect due to differences in the thickness of the core and wall layers. The proposed Lagrange analysis can reveal the behavior of the propagation speed. Based on the results of the Lagrange approach, the highest velocity is obtained at a thickness of 80 with a maximum speed of 2.395 km/s. At the same time, cores with dimensions of 70 mm and 90 mm are not recommended for use because they have a low testing accuracy. New methods need to be developed to predict wave refraction due to the influence of EPS. The non-destructive tests using the Ultrasonic Pulse Velocity method and the Lagrangian numerical test successfully predict the sandwich panel's thickness. The results of this study contribute to the non-destructive test procedure, especially in determining homogeneity and the dimensions of the effective thickness of the structural walls (cores and layers) that have been installed in the field quickly, cheaply, accurately, and briefly.

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https://dx.doi.org/10.30737/ukarst.v6i2.3545

References

[1] Badan Standarisasi Nasional Indonesia, "SNI 2847-2019 : Persyaratan Beton Struktural untuk Bangunan Gedung," *BSN*, 2019.

[2] A. Kaya and F. Kar, "Properties of concrete containing waste expanded polystyrene and natural resin," *Constr. Build. Mater.*, vol. 105, pp. 572–578, 2016, doi: 10.1016/j.conbuildmat.2015.12.177.

[3] A. San-Antonio-González, M. Del Río Merino, C. Viñas Arrebola, and P. Villoria-Sáez, "Lightweight material made with gypsum and extruded polystyrene waste with enhanced thermal behaviour," *Constr. Build. Mater.*, vol. 93, pp. 57–63, 2015, doi: 10.1016/j.conbuildmat.2015.05.040.

[4] D. S. Babu, K. Ganesh Babu, and T. H. Wee, "Properties of lightweight expanded polystyrene aggregate concretes containing fly ash," *Cem. Concr. Res.*, vol. 35, no. 6, pp. 1218–1223, 2005, doi: 10.1016/j.cemconres.2004.11.015.

[5] H. R. Tabatabaiefar, B. Mansoury, M. J. Khadivi Zand, and D. Potter, "Mechanical properties of sandwich panels constructed from polystyrene/cement mixed cores and thin cement sheet facings," *J. Sandw. Struct. Mater.*, vol. 19, no. 4, pp. 456–481, 2017, doi: 10.1177/1099636215621871.

[6] S. N. Priya and C. G. Sivakumar, "Experimental Investigation of the Properties of Light Weight Concrete Wall Panels," *Int. J. Mech. Eng.*, vol. 6, no. 3, pp. 401–405, 2021.

[7] E. Matsuo, "Properties of Lightweight Concrete Using Expanded Polystyrene as Aggregate," *Int. J. Environ. Rural Dev.*, vol. 10, no. 2, pp. 8–13, 2019, doi: https://doi.org/10.32115/ijerd.10.2_8.

[8] J. Suizi, C. Wanlin, L. Zibin, D. Wei, and S. Yingnan, "Experimental study on a prefabricated lightweight concrete-filled steel tubular framework composite slab structure subjected to reversed cyclic loading," *Appl. Sci.*, vol. 9, no. 6, p. 1264, 2019, doi: 10.3390/app9061264.

[9] M. Pekgöz and İ. Tekin, "Microstructural investigation and strength properties of structural lightweight concrete produced with Zeolitic tuff aggregate," *J. Build. Eng.*, vol. 43, no. April, 2021, doi: 10.1016/j.jobe.2021.102863.

[10] Y. Xu, L. Jiang, J. Xu, and Y. Li, “Mechanical properties of expanded polystyrene lightweight aggregate concrete and brick,” *Constr. Build. Mater.*, vol. 27, no. 1, pp. 32–38, 2012, doi: 10.1016/j.conbuildmat.2011.08.030.

[11] B. Demirel, “Optimization of the composite brick composed of expanded polystyrene and pumice blocks,” *Constr. Build. Mater.*, vol. 40, pp. 306–313, 2013, doi: 10.1016/j.conbuildmat.2012.11.008.

[12] P. L. N. Fernando, M. T. R. Jayasinghe, and C. Jayasinghe, “Structural feasibility of Expanded Polystyrene (EPS) based lightweight concrete sandwich wall panels,” *Constr. Build. Mater.*, vol. 139, pp. 45–51, 2017, doi: 10.1016/j.conbuildmat.2017.02.027.

[13] S. Suryani and N. Mohamad, “Structural Behaviour of Precast Lightweight Foamed Concrete Sandwich Panel under Axial Load : An Overview,” *Int. J. Integr. Eng.*, vol. 4, no. 3, pp. 47–52, 2012.

[14] B. Ji, Z. Hu, W. Zhou, J. Chen, and X. Wang, “Experimental study on the behavior of lightweight aggregate concrete filled circular steel tubes under axial compression,” *Int. Conf. Adv. Exp. Struct. Eng.*, vol. 43, pp. 5225–5242, 2007, doi: https://doi.org/10.1007/s13369-018-3066-9.

[15] S. Tengku Fitriani, “Lightweight high strength concrete with expanded polystyrene beads,” *Mektek*, vol. 8, no. 1, pp. 9–15, 2006.

[16] N. Mohamad, W. Omar, and R. Abdullah, “Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) tested under axial load: Preliminary results,” *Adv. Mater. Res.*, vol. 250–253, pp. 1153–1162, 2011, doi: 10.4028/www.scientific.net/AMR.250-253.1153.

[17] N. Mohamad, A. I. Khalil, A. A. Abdul Samad, and W. I. Goh, “Structural behavior of precast lightweight foam concrete sandwich panel with double shear truss connectors under flexural load,” *ISRN Civ. Eng.*, 2014, doi: 10.1155/2014/317941.

[18] Y. H. M. Amran, R. S. M. Rashid, F. Hejazi, N. A. Safiee, and A. A. A. Ali, “Response of precast foamed concrete sandwich panels to flexural loading,” *J. Build. Eng.*, vol. 7, pp. 143–158, 2016, doi: 10.1016/j.jobe.2016.06.006.

[19] E. Negahban, A. Bagheri, A. Al-Dujaili, and J. Sanjayan, “Insulation failure of lightweight composite sandwich panels exposed to flame,” *Fire Mater.*, vol. 44, no. 7, pp. 943–952, 2020, doi: 10.1002/fam.2897.

[20] A. Kan and R. Demirboğa, "A new technique of processing for waste-expanded polystyrene foams as aggregates," *J. Mater. Process. Technol.*, vol. 209, no. 6, pp. 2994–3000, 2009, doi: 10.1016/j.jmatprotec.2008.07.017.

[21] K. Komloš, S. Popovics, T. Nürnbergerová, B. Babál, and J. S. Popovics, "Ultrasonic pulse velocity test of concrete properties as specified in various standards," *Cem. Concr. Compos.*, vol. 18, no. 5, pp. 357–364, 1996, doi: 10.1016/0958-9465(96)00026-1.

[22] J. A. Bogas, M. G. Gomes, and A. Gomes, "Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method," *Ultrasonics*, vol. 53, no. 5, 2013, doi: 10.1016/j.ultras.2012.12.012.

[23] ASTM, "ASTM C597-16-Pulse Velocity Through Concrete," *United States Am. Soc. Test. Mater.*

[24] BSI Standards, "Testing concrete — Part 4: Determination of ultrasonic pulse velocity," *Br. Stand.*, vol. 3, no. April, p. 18, 2004.

[25] F. Durst, D. Milojevic, and B. Schoenung, "Eulerian and Lagrangian predictions of particulate two-phase flows.," *Appl. Math. Model.*, vol. 8, no. 2, pp. 101–115, 1983, doi: https://doi.org/10.1016/0307-904X(84)90062-3.

[26] G. Gouesbet and A. Berlemont, "Eulerian and Lagrangian approaches for predicting the behaviour of discrete particles in turbulent flows," *Prog. Energy Combust. Sci.*, vol. 25, no. 2, pp. 133–159, 1999, doi: 10.1016/s0360-1285(98)00018-5.

[27] Y. Gao, J. H. Ko, and H. P. Lee, "3D coupled Eulerian-Lagrangian finite element analysis of end milling," *Int. J. Adv. Manuf. Technol.*, vol. 98, no. 1–4, pp. 849–857, 2018, doi: 10.1007/s00170-018-2284-3.