Research Article

Effect of resin amount on the damping properties of polymer concrete

Arif Ulu [a,*]

[a] Department of Mechanical Engineering, İstanbul Aydın University, 34295 İstanbul, Türkiye

ABSTRACT

In the construction and infrastructure sector, efforts are being made to find faster and more efficient materials. Polymer concrete (PC) challenges traditional concrete with its fast setting, durability and abrasion resistance. While studies on PC strength are abundant in the literature, studies on the effects of resin amount on damping capacity are fewer than mechanical performance. In this paper, the effect of resin proportion on damping capacity is investigated by modal tests. PC mixtures in the production with different resin proportions (11–19%) were poured into molds of 10x25x500 mm, using aggregates of up to 3.15 mm in size. After 14 days, the natural frequency and damping ratios of the specimens up to 1000 Hz were determined in modal tests. While the damping ratio (DR) decreased in resin contents up to 17%, the results of the specimens with 19% resin ratio increased. However, when the products with the same resin ratio are analyzed, the random distribution of the aggregate affects the damping capacity. The main reason of negative correlation between resin amount and DR is the filler amount in the mixture. Because of the production consistency, fluidization of all the mixtures is prevented by adding fillers. Therefore, the impact of the resin amount on DR is limited or even negative. Besides that, to compare measurement results finite element method (FEM) analyzes are conducted. It can be said that the natural frequencies are not suited well especially in high frequency ranges due to frequency dependent properties (visco-elastic) of PC.

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1. Introduction

Polymer concrete (PC) has gained more importance in infrastructure industry as a powerful material for last decades. Due to its ability to be less labor-efficient and higher mechanical strength, higher chemical resistance then classical concrete, it is utilized for drainage channels, cable channels, even more machine tool bed. While the cement-based concretes have maximum 30–35 MPa compressive strength and 7–8 MPa flexural strength, polymer concretes have 90–100 MPa and 20–25 MPa respectively (Cakir 2022). Besides aggregates, polymer-based resin is combined with accelerator, hardener, maybe additives. In the industry, different types of resin are utilized such as epoxy, unsaturated polyester. Resin concrete is manufactured by blending a monomer or resin with aggregate, and subsequently polymerizing or curing the mixture. Among these materials, resin concrete, widely employed, utilizes matrix materials such as unsaturated polyester, epoxy, and acrylic resins, while pebble and sand serve as the aggregate materials for the resin concrete. By using different types of resin and aggregates ratios, one can hold different mechanical properties, as well as damping.

Damping in PC remains a subject of ongoing investigation among researchers, while the damping mechanism of real structures remains an incompletely resolved topic (Rasa and Özyazıcıoğlu 2021). Alterations in the damping ratio (DR) can be achieved by introducing fibers or combining different material types. Damping is attributed to phenomena occurring within the material grains, leading to energy loss. Factors such as grain

* *Corresponding author*. Tel.: +90-212-444-1-428 ; E-mail address: arifulu@aydin.edu.tr (A. Ulu)
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boundary cracks, intragranular cracks, and interstitial voids in coarse solid aggregate contribute to increased energy dissipation, resulting in improved damping (Chinnuraj 2021). Various techniques, including damping ratio, loss factor, decay constant, and quality factor, are employed to assess the damping properties of materials. The study by Kim et al. (1995) explores mechanical properties by varying the size, compact ratio, and ingredient contents. A damping ratio of 1.3–1.4% is obtained for pebble content. Orak (2000) produces PC samples with a fixed 20% unsaturated polyester resin and different aggregate compositions, finding PC suitable for machine tool beds due to its viscoelastic nature. However, no correlation between filler composition and damping is identified. Cortes and Castillo (2007) compare epoxy resin polymer concrete (10%) with gray cast iron for machine tool applications, showing that PC has advantages in damping ratio (0.79–2.21%). Suh and Lee (2008) develop a machine tool bed polymer concrete with 10% polyester resin, yielding a DR between 2.93–5.69%. Bedi and Brar (2014) investigate the impact of polyester resin content (16–24% w.t) in PC on the loss factor using a DMA device, presenting equivalent damping ratios in Table 1.

Table 1. Summary of the literature about damping.

Literature	Resin type	Resin ratio (wt%)	Aggregate size	Aggregate+Filler	Damping ratio (%)	Method
Kim et al. (1995)	Epoxy	7.5	Mesh Size 6	Sand + Pebble	1.3–1.4	Log decrement
Li et al. (1996)	Epoxy	4.9*-13*	0.08-11.1mm	Granite + Rubber	2.18–2.67**	DMA
Orak (2000)	Polyester	20	0.25 – 8 mm	Sand + Quartz	1.66–2.86	Log decrement
Cortes and Castillo (2007)	Epoxy	10	0-10 mm	Basalt + Quartz	0.79–2.21	Log decrement
Suh and Lee (2008)	Polyester	10	Mesh Size 12	Sand	2.93–5.69	Half-power bandwidth
Bedi and Brar (2014)	Polyester	16-24	0.225-0.6 mm	Sand+$CaCO_3$	2.8–7.6 (20 Hz)** 2.74–7.28 (40 Hz)**	DMA
PC with additional materials						
Bignozzi et al. (2002)	Polyester	12	0.075-2 mm	Silica + $CaCO_3$ + Fibers	Varying with temperature	DMA
Jeon et al. (2015)	Epoxy	20	0.25-1.2 mm	Unknown + Carbon Fiber	0.75–1.0**	
Hwang et al. (2019)	Epoxy	20-30	0.25-1.2 mm	Sand + Recycled PEI	0.8–1.0**	Half-power bandwidth
Trancossi et al. (2022)				EPUMENT 140 Series	0.46–0.99**	Half-power bandwidth
Bai et al. (2009)	Epoxy	8-16	0-10 mm	Granite proportion + Glass Fiber	0.16–0.33	Half-power bandwidth
Damping studies of cement concrete						
	Concrete Type		Aggregate size	Fiber of filler	Damping ratio (%)	Method
Mo et al. (2020)	C30		Max 20 mm	PP fiber & Rubber powder (380μm)	2.64–4.72	Log decrement
Li and Xiao (2021)	C30		Max 25 mm	Recycled Aggregates	3.1–4.6	Half-power bandwidth
Li et al. (2021)	New to old concrete		Max 25 mm	Recycled Aggregates	6.0–8.0	Half-power bandwidth
Xi et al. (2021)	UHPC		Fine modulus 2.5	Steel Fiber	2.7–3.7	Half-power bandwidth & Log decrement

* Volume percentage

** Calculated equivalent damping ratio

Research on the DR effectiveness of different materials on pure PC is found in the literature, including recycled materials or fibers. Jeon et al. (2015) use epoxy resin (20%) with carbon fibers for railway slab noise, concluding that the loss factor increases with the weight percentage of fibers, with fiber PC having a 4dB advantage in noise reduction compared to PC alone. Hwang et al. (2019) address railway-induced slab noise mitigation using recycled polyetherimide (PEI), finding no significant variation in dynamic characteristics concerning the weight percentage of epoxy resin (20–30%). Therefore, they study variations in PEI content to enhance damping performance. Troncossi et al. (2022) aim to enhance the damping capacity of machine beds using EPUMENT 140 polymer concrete, calculating the damping ratio of pure PC content through modal analysis.

Besides damping studies of PC, it has also been investigated damping of traditional concrete by utilizing fibers, fillers, nano-tubes etc. It is stated in the research of Chi et al. (2019), controlling the filler effect in cement matrix composites involves managing the particle size and volume fraction of the inorganic powders. The presence of multiple phase boundaries and interfaces between nanotubes and the cement matrix increases the likelihood of interfacial slippage, leading to elevated energy dissipation, as well. In the results of Mo et al. (2020), it is found that addition of rubber powder enhances damping capacity (2.64–4.72%) of polypropylene fiber reinforced concrete (PFRC) but comes at the cost of reduced compressive strength and an increase in peak strain within the concrete. Li and Xiao (2021) study employs free vibration attenuation as a method to assess the damping characteristics (3.1–4.6%) of recycled concrete at varying rates of recycled aggregate replacement. Li et al. (2021) research investigates the impact of the interface in recycled concrete on damping performance by examining specimens comprising bonded new and old concrete. The study utilizes semi-precast concrete specimens incorporating both old and new concrete. The damping ratio falls within the range of 0.005 to 0.007 at high-frequency positions and 0.06 to 0.08 at low-frequency positions. Xi et al. (2021) explored four damping testing techniques (T-type method, cantilever beam method, simply supported beam method, and suspension method), three analytical approaches (half-power bandwidth method, INV damper method, time-domain method), and examined the impact of sampling frequencies on damping results.

Given damping studies in this paper are tabulated in Table 1. As seen in the literature, determining DR of PC with respect to resin ratio is an attractive content. In this regard, polyester resin ratio effect on damping issue is investigated. In this paper, PC specimens with resin ratios of 11–19% are prepared, the specimens are fixed to the experimental setup to conduct modal testing. Samples of polymer concrete are fixed at one end, then it is subjected to excitation using a hammer. Vibration data is acquired using a data logger and later processed with the 'Signal Processing Toolbox' of Matlab. The experimental Frequency Response Function (FRF) responses are analyzed to determine the stable modes and damping. Lastly, calculated damping ratios of beams are listed.

2. Materials and Method

PC samples are prepared in the polymer concrete channel factory of Mert Casting Inc company. Unsaturated polyester resin (UPR) is available on market, and it is selected as binder due to its lower cost comparing to epoxy resin. General purpose resin, details given Table 2, can wet fillers well. UPRs are thermosetting and can solidify from a liquid under the certain conditions. The main polymer chain of this resin has ester bonds, which are created by the compression of a multifactorial alcohol compound and its multifactorial acid.

Granulometry of silica-sand aggregates (Fig. 1), density 2.6 g/cc with 0.1–3.15 mm grain size, are adjusted according to Fuller curve and its chemical composition is given in Table 3. Sample recipes cannot be shown here due to company restrictions.

Table 2. Technical properties of resin (Cakir 2022).

Properties	Values
Flexural strength in 5% strain (MPa)	51.6
Compressive strength (MPa)	34.1
Impact strength (J/m)	12.9
Viscosity (mPa.s)	659
Shore hardness	80
Tensile modulus (MPa)	527
Density (g/cm^3)	1.225

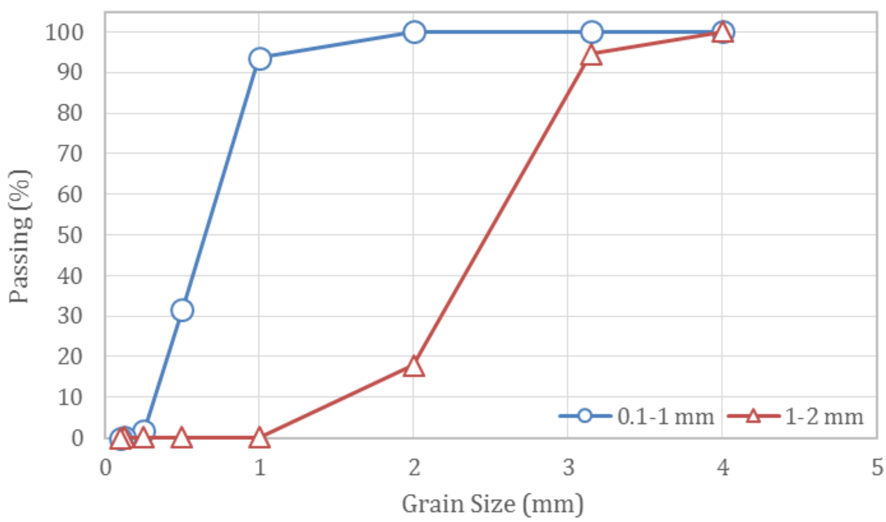


Fig. 1. Grain size distribution of aggregates.

Table 3. Chemical compositions of aggregates.

Chemicals	Aggregates		
	0.1–1 mm	1–2 mm	2–3.15 mm
MgO (%)	0.10	0.06	0.06
Al_2O_3 (%)	0.245	1.86	1.86
SiO_2 (%)	98.86	94.15	94.15
CaO (%)	0.01	0.39	0.39
Fe_2O_3 (%)	0.148	0.46	0.46
SO_3 (%)	-	0.10	0.10
K_2O (%)	0.03	1.56	1.56
Na_2O (%)	0.02	1.12	1.12
Loss (%)	0.587	0.30	

Furhermore, Calsite ($CaCO_3$) and AAP (acetylacetone peroxide) is utilized for filler and hardener. AAP, a quick-setting peroxide that is often used to harden UPRs, was applied. Technical details of AAP are given in Table 4. Apart from the AAP, Methyl Ethyl Ketone Peroxide (MEKP) could also be chosen for hardener (Cakir et al. 2020).

In order to activate UPR in room temperature (20 °C) Cobalt naphthenate, whose technical specifications are tabulated in Table 5, was selected as AAP accelerator. Usually, accelerators increase the system's heat, which makes resin reactions quicker. All components in each mixture are added at a consistent weight ratio.

Prior to use, all aggregates are thoroughly cleaned with water to prevent any contamination. After the aggregates are prepared, they are filled into the production machine. Hardener and accelerator are added to the aggregate mixture that comes out of the device along with calcite and resin and filled into the molds as seen in Fig 2(a). According to grain size, samples dimensions are determined in 10x25x500 mm as seen in Fig. 2(c). As stated in Cakir (2022), PC achieve over 80% of their mechanical strength in the initial three days, and there is minimal alteration in their long-term strength beyond the seventh day. Therefore, all of the samples are utilized after fourteen days with curing at room temperature. Furthermore, the mixtures were made by machine and the amount of accelerator was increased specially only for this study. The mixture coming out homogeneously from the end of the machine was immediately poured into the molds. Thus, rapid curing was achieved, and precipitation formation was prevented.

Table 4. Technical properties of hardener (Cakir 2022).

Properties	Values
Flash point	> 60 °C
Density, 20 °C	1055 kg/m³
Viscosity, 20 °C	21 mPa.s
Self-accelerating decomposition temperature (SADT)	60 °C
Total active oxygen	4–4.2%
Peroxide content	33%
Diethylene glycol + water + diacetone alcohol	67%

Table 5. Technical properties of accelerator (Cakir 2022).

Properties	Values
Density (at 20 °C)	0.92 g/cm³
Viscosity (at 20 °C)	300 mPa.s
Self-accelerating decomposition temperature (SADT)	≥ 150 °C
Flash point	62 °C
Cobalt content	1.50%

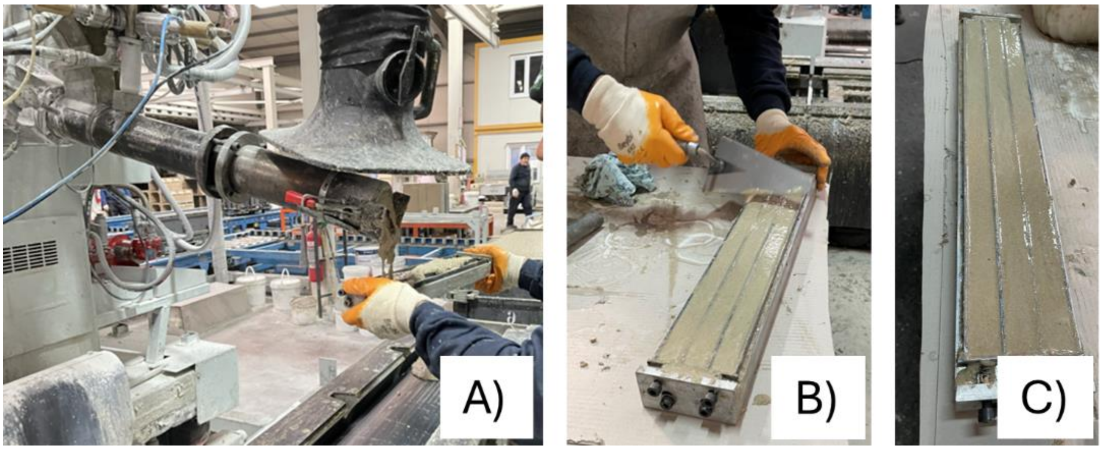


Fig. 2. Preparation of samples: (a) Filling the mold; (b) Flattening the surface; (c) Curing.

In the area of structural engineering, analyzing dynamic systems frequently focuses on two key components. Comprehending a system's natural frequency and damping ratios yields thorough understanding of its behavior. To avert possible harm, it is important to refrain from driving a system within the frequency range of 0.8 to 1.25 times its natural frequency. The natural frequencies of structures with established mass and stiffness may be computed or gauged using uncomplicated analytical techniques. Unlike natural frequency, determining the damping ratio is rather arduous and necessitates analytical assumptions. As a result, multiple damping models have been documented in the literature, representing the intricacy of this component.

These fundamental parameters can be determined through experimentation, even in the absence of an analytical model and specific structural or material details. Modal analysis, which is an experimental technique, is utilized to acquire the damping ratios and natural frequency of a system by observing the signal relationship between input and output. A hammer generates the input signal, allowing the system to become excited across all frequencies. The output signal of the system comprises the responses measured at specific points through accelerometers or displacement sensors. When there is a single input and one output channel, it is termed SISO (Single Input Single Output); whereas, if multiple input and output channels are involved, it is referred to as MIMO (Multiple Input Multiple Output).

Once the input/output signals have been obtained, it is essential to carry out a careful analysis, and in the event of unreal results, to repeat the experiments. The first step is to demonstrate a high correlation, called coherence, between the input and output signals. The coherence amplitude ranges from 0 to 1. Low values signify a weak correlation between input and output channels, which may be attributed to factors such as noise or gaps in the excitation spectrum at specific frequencies. Values approaching 1 indicate robust and representative measurements. Peaks observed in frequency-amplitude plots correspond directly to the natural frequencies of the system. In cases where multiple peaks are present, phase amplitude curves can be used. If there is instability around the natural frequencies, finite element programs or analytical models can be used. The stability diagram is a visual representation commonly illustrating the relationship between damping ratio and natural frequency for each mode in the examined structure. Its significance lies in validating the trustworthiness of modal analysis outcomes by pinpointing stable and accurate regions within the frequency-damping space for identified modes. Any instabilities or uncertainties concentrated around specific frequencies become apparent on the diagram. If a mode is situated within an unstable region, it could suggest problems like measurement noise, insufficient excitation, or numerical errors in the analytical process. In essence, the stability diagram is instrumental in assessing and enhancing the precision of modal analysis results in the realm of structural dynamics. By considering the above factors, the natural frequencies of the system can be accurately determined.

In the experimental arrangement, the molded samples were tied to a stable table by using a vice to adhere to the fixed boundary condition. The accelerometer was positioned at the end of the PC beam, as illustrated in the Fig. 3. However, the PC surface made it difficult to attach the accelerometer directly onto the rod. To resolve this problem, a plastic clamp (Fig. 3(a)) was utilized to fasten the accelerometer to the beam. Throughout the experiments, the accelerometer and the hammer were connected to a data acquisition system (Fig. 3(b)).

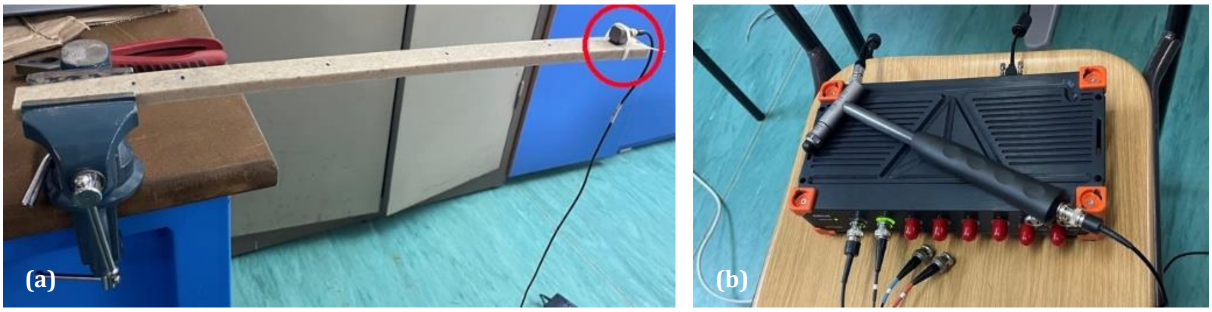


Fig. 3. Experimental Setup: (a) PC beam with accelerometer; (b)Data logger and impact hammer.

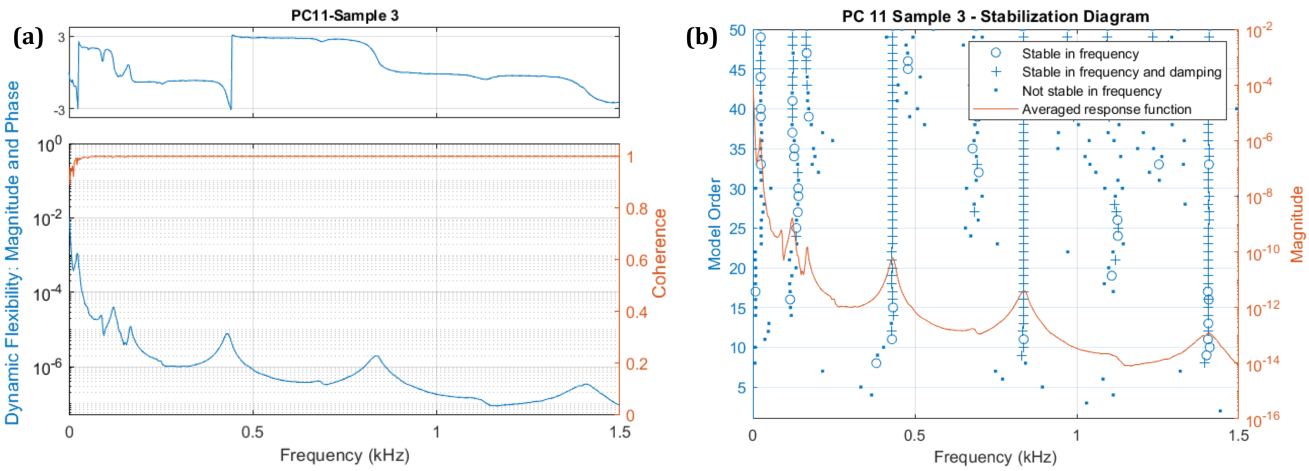


Fig. 4. Plots from modal testing: (a) Resonance, phase and coherence; (b) Evaluating frequencies and damping ratios.

The experimental procedures implemented the SIRIUS® HD-ACC data logger by Dewesoft, which can measure within the 0-20kHz range. The Kistler IEPE accelerometer has a sensitivity of 101.3 mV.g^{-1} within the ±50g range. The IH-02 series from DJB Instruments acted as the actuator for the PC beam, exhibiting a 2.48 mV.N^{-1} sensitivity.

3. Results and Discussion

Table 6 shows the four natural frequencies and four damping ratio values calculated in modal tests. For PC specimens, the number in the middle indicates the resin amount and S1, S2, S3 at the end indicates the number of specimens. Specimen PC_13_S3 could not be tested because it broke during transportation. Firstly, if the natural frequency results are analyzed; 1st natural frequencies were calculated as 24.36 Hz on average between 21.08-27.79 Hz. On the other hand, damping ratios were 6.12% on average and varied between 3.56-9.67%. The average, maximum and minimum values of other natural frequencies and damping ratios are given in the table. Fig. 5 is plotted by visualizing the damping ratios read from the table. Even in high frequencies, PC performs a good damping capacity considering other materials like gray cast iron (Orak 2000). As can be seen in the Fig. 5, a significant relationship was found between increasing the polyester ratio and the damping ratio until 17% polyester ratio. When 19% resin proportion is considered, an increment in the damping ratio is seen in Fig 5. Up to %17 resin ratio effects on the damping are plotted in Fig. 6. When samples with the same resin ratio are examined, the random distribution of the aggregates can vary the damping capacity. Even at 19% resin amount, the spread in the damping ratio was observed to be less than the other ratios. This showed that the effect of aggregate distribution was broken.

Table 6. Modal test results.

PC Names	1.Mode (Hz)	2.Mode (Hz)	3.Mode (Hz)	4.Mode (Hz)	DR_1 (%)	DR_2 (%)	DR_3 (%)	DR_4 (%)
PC_11_S1	23.66	123.17	457.66	890.42	6.44	3.94	1.94	1.95
PC_11_S2	24.95	121.96	476.27	918.64	5.57	3.95	2.00	1.75
PC_11_S3	23.53	121.68	430.97	835.92	8.75	3.94	1.98	2.00
PC_13_S1	25.49	183.54	485.85	940.28	4.59	1.92	1.93	1.91
PC_13_S2	27.79	125.30	539.06	1018.70	8.18	4.02	1.87	2.03
PC_13_S3	-	-	-	-	-	-	-	-
PC_15_S1	24.77	123.07	447.44	866.90	4.42	4.45	1.88	1.80
PC_15_S2	24.08	120.04	457.28	886.92	6.10	2.90	4.38	1.92
PC_15_S3	24.27	121.40	457.40	895.78	4.14	4.55	1.86	0.79
PC_17_S1	25.60	125.04	443.22	883.00	3.64	4.57	1.29	1.30
PC_17_S2	24.46	120.22	440.27	864.60	3.56	2.63	2.27	3.28
PC_17_S3	26.23	125.59	460.81	894.59	4.89	5.29	1.99	1.43
PC_19_S1	21.08	121.51	428.78	836.48	7.86	3.36	1.55	1.53
PC_19_S2	23.43	123.29	441.03	860.08	7.85	4.26	1.83	1.65
PC_19_S3	21.63	119.95	387.66	756.84	9.67	4.55	2.10	3.12
Minimum	21.08	119.95	387.66	756.84	3.56	1.92	1.29	0.79
Maximum	27.79	183.54	539.06	1018.70	9.67	5.29	4.38	3.28
Mean	24.36	126.84	453.84	882.08	6.12	3.88	2.06	1.89

Compared to the studies on pure PC, resin has the greatest contribution on damping capacity, while fine aggregate and filler have the least factor (Bedi and Brar 2014). Moreover, an increment trend in damping is seen until 20% resin proportion by considering maximum 0.6 mm grain size. Orak (2000) indicates that it remains uncertain whether the damping properties of polymer concrete vary based on the filler composition that is maximum 5mm grain size. The effect of resin amount on PC damping is not investigated due to constant at 20%. On the other hand, it is found that the granite proportion, which has maximum 10 mm grain size, is the most significant factor on the glass fiber reinforced PC (GFRPC) in the study of Bai et al. (2009), while the glass fiber dosage has the least impact on the damping ratio. Furthermore, it is mentioned that raising the epoxy dosage leads to a higher damping GFRPC, as the damping ratio of epoxy resin surpasses that of granite particles. As can be seen from the literature, the amount of resin is the most effective factor when using fine aggregates (0.6mm), whereas the grain size is the most effective factor when using coarse aggregates (10mm). In the study using 0-5mm aggregate, no significant relationship is found between aggregate size and damping capacity when the resin ratio is kept constant. In general terms, it can be said that even in the worst case, PC has a damping ratio even higher than that of cement-based concrete with admixtures (Mo et al. 2020; Xi et al. 2021).

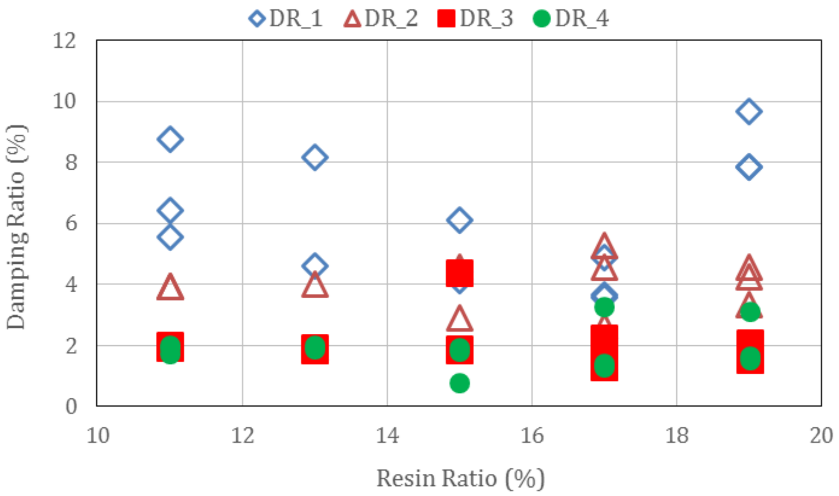


Fig. 5. Comparison of damping ratios.

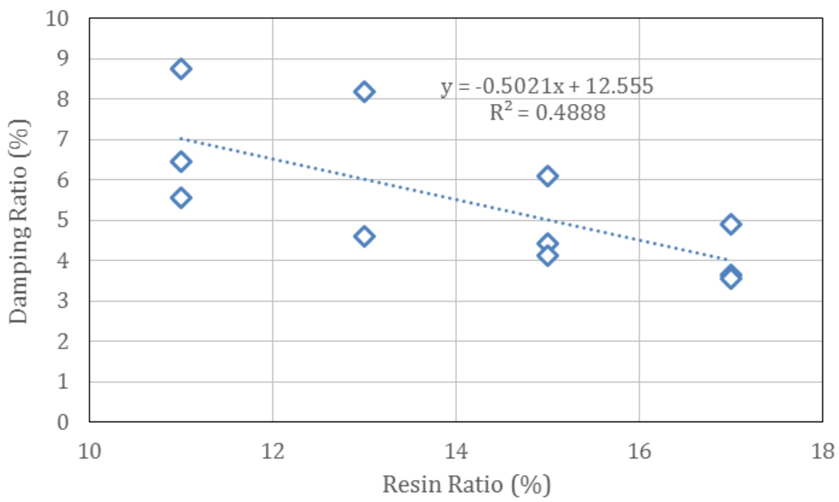
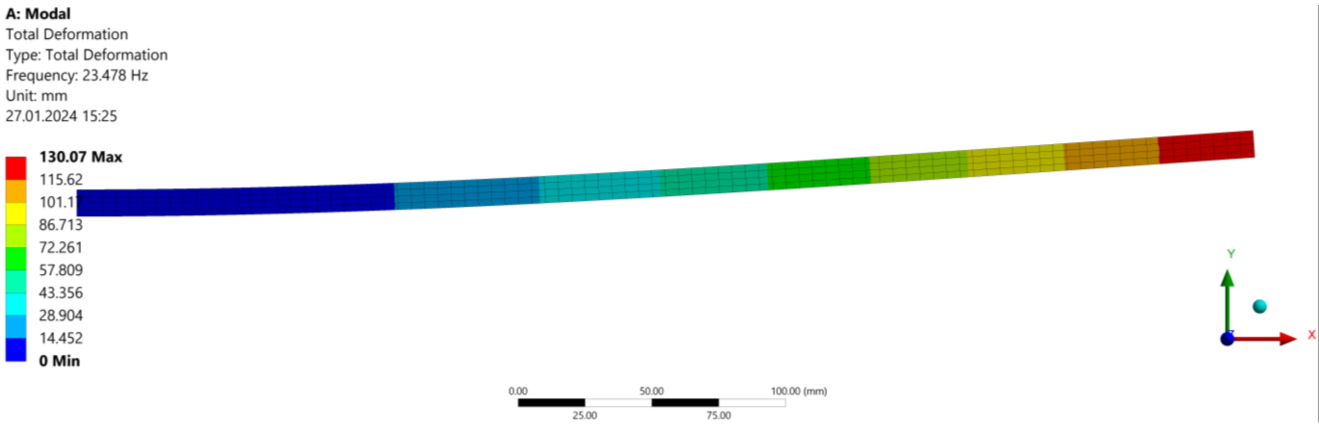


Fig. 6. Deviation of first damping ratios up to 17% resin amount.

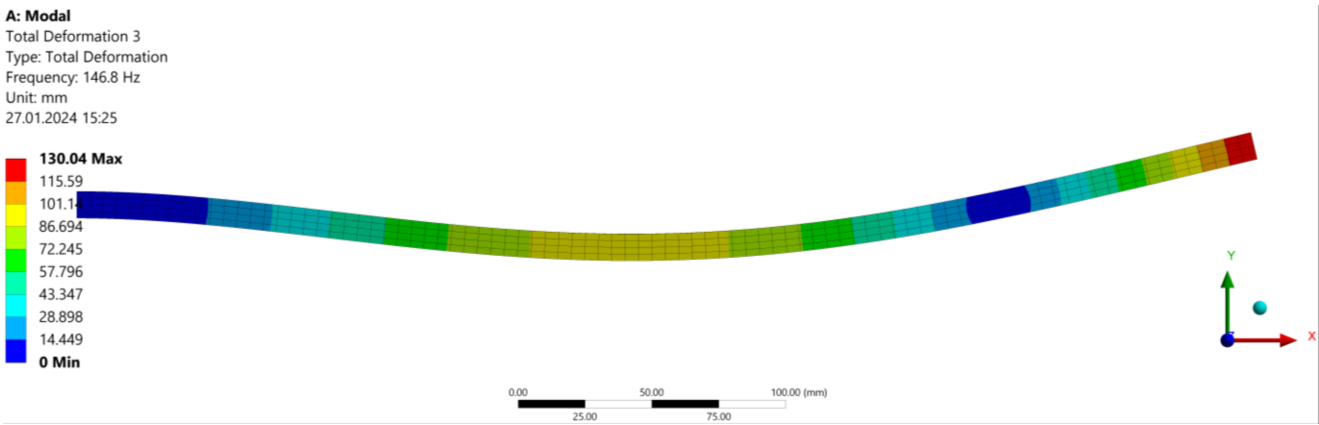
Moreover, FEM analyses were performed for PC11 series to show the consistency of the experiments in ANSYS. The modulus of elasticity was taken as 17 GPa, Poisson's ratio as 0.18, density as 2150 kg/m³. Based on PC11_S1 coded mixture, experimental and FEM results were compared in Table 7, while the first to fourth mode shapes were shown in Fig. 7. When the table was analyzed, inconsistency was observed in other modes except the first natural frequency. The difference between results were calculated between 11.50–16.10%. The reason for this is that the resin and therefore the polymer concrete shows visco-elastic properties. In other words, the modulus of elasticity varies depending on the frequency.

Table 7. Comparison of the results of PC11_S1.

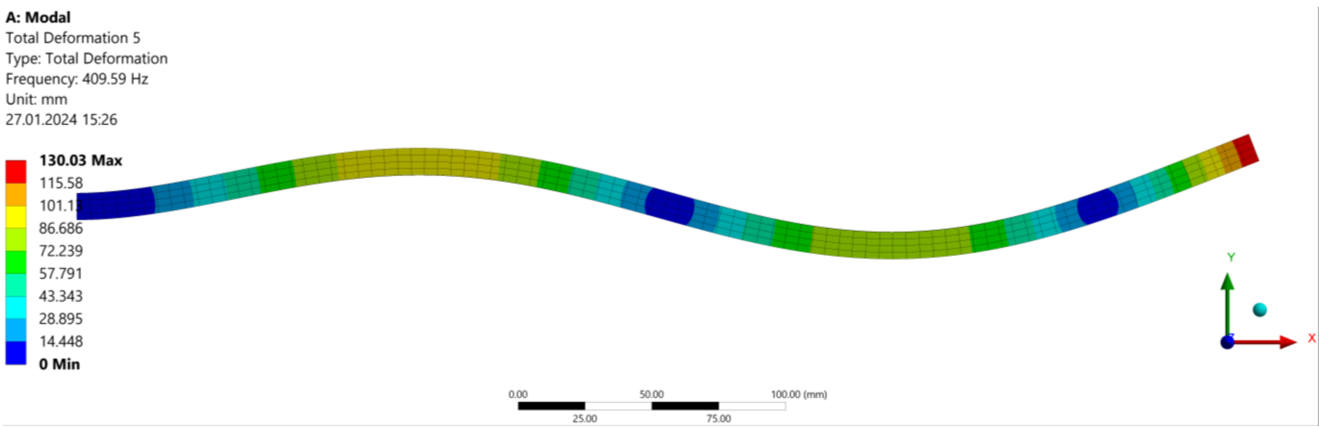
Method	1.Mode (Hz)	2.Mode (Hz)	3.Mode (Hz)	4.Mode (Hz)
FEM	23.48	146.8	409.59	798.57
Experimental	23.66	123.17	457.66	890.42
Difference	0.77%	16.10%	11.74%	11.50%



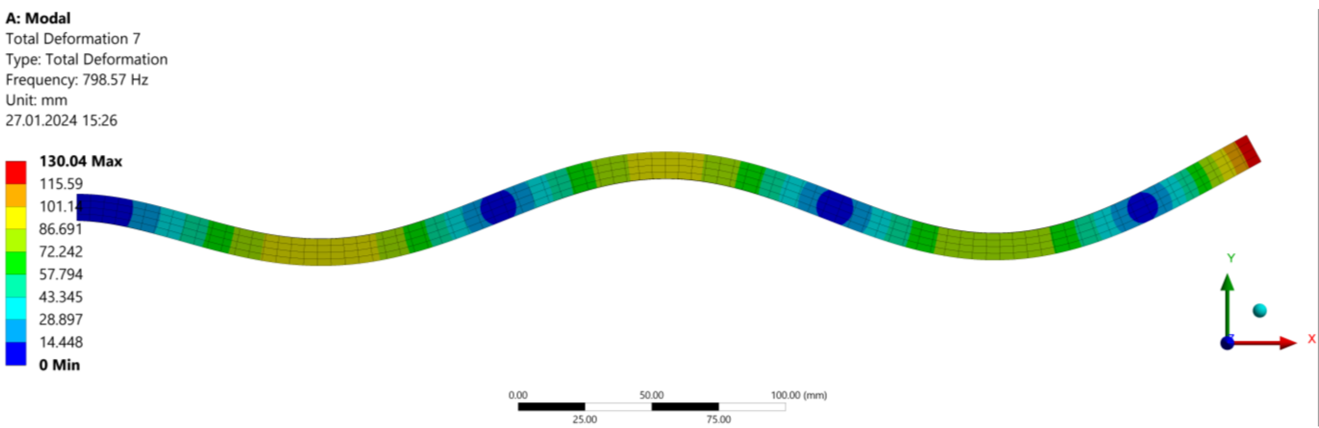
a) First Mode



b) Second Mode



c) Third Mode



d) Fourth Mode

Fig. 7. FEM mode shape results of PC11_S1.

4. Conclusions

In this study, the effect of polyester resin amount on PC damping ratio was investigated. Aggregate sizes up to 3.15 mm were used and specimens were prepared by increasing the resin ratio and decreasing the coarse aggregate ratio. The specimens, which were fixed to the rigid table by providing the fixed-free boundary condition, were excited with a modal hammer, and the modal frequency and damping ratios were calculated with the help of Matlab software. When the results were analyzed, while the resin ratio increased up to 17%, the first damping ratio decreased and an increase of 19% resin ratio was recorded. However, when the same resin ratio samples were analyzed, it was found that the damping ratio was highly variable and that the randomly distributed sand grains were effective in determining the damping ratio. The least spread in damping capacity was observed at 19% resin content, due to low random aggregates distribution. Opposite to the literature, a negative correlation was obtained between damping ratio and resin amount. Because existing production recipe lists were used in production instead of certain experimental design methods. If the resin ratio increases in daily production, segregation begins, and fluidity increases. Therefore, leakages occur in the molds and the mixture is not distributed homogeneously in the products. The filler ratio is increased to reduce fluidity, prevent leakages, and prevent segregation. Another remarkable result is that the natural frequencies and FEM results are different. It was observed that the discrepancy of the results at high frequencies increased due to the visco-elastic properties of polymer concrete. In further studies the effects of coarse, fine, calcite and resin on the damping capacity of PC can be investigated by means of a design of experiments (DoE). In addition, the effect of visco-elastic material properties on the dynamic behavior of PC can be investigated.

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Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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