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Evaluation of Damping Properties of Recycled Polymer Concretes Intended for Machine Tool Structures

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Abstract

The aim of this study is to evaluate the damping properties of manufactured polymer concretes containing a recycled fraction (used garnet from waterjet cutting) by comparing selected properties, particularly Young's modulus, with the Young's modulus of grey cast iron. The authors sought to answer the following question: Is it possible to use polymer concretes as a structural material or as a material preventing displacement caused by the operation of lathes?

In the experimental part of the study, epoxy resin-based polymer concretes were produced. The density, flexural strength, compressive strength, and Young's modulus of the manufactured polymer concretes containing a recycled fraction were evaluated and compared with those of ductile cast iron. Differences in the damping properties between cast iron and the polymer concretes were also identified and assessed, taking into account the logarithmic decrement of damping.

Keywords: composites, polymer concrete, recycling, garnet, damping properties, machine tool structures, cast iron

1. Introduction

Long-term observations indicate that the structures of machines and equipment, including lathes, undergo continuous modifications and structural-material changes. This is related to the fact that existing machine tools, due to their function and design, can only be improved rather than fundamentally redesigned.

Traditional lathe construction is associated with the use of cast iron components made from various grades of grey cast iron for individual structural elements. Cast iron, as a structural material for this type of machine tool, is a highly effective solution as a consequence of its favorable properties, such as vibration damping capability, excellent tribological characteristics, and significant weight, which ensures the stable positioning of lathes. Nonetheless, cast iron is susceptible to corrosion. The turning process involves the movement of the cutting tool and its interaction with the workpiece. Therefore, it is extremely important that lathes are made from heavy materials that guarantee operational stability.

Recent research and technological development show a clear tendency to move away from traditional cast iron castings toward mineral castings, known as polymer concretes, owing to their superior dynamic properties [1]. Polymer concrete is a composite material consisting of fine inorganic aggregate particles such as basalt, fly ash, spodumene, sand, gravel or chalk, bonded together with resin [2]. The typical volume ratio of filler (aggregate) to binder (resin) is approximately 9:1 [1,2].

An improperly secured machine tool (not fixed to the foundation) or a lathe made from lightweight innovative materials [1,2], such as steel profiles filled with polymer or polymer concrete, may operate improperly. During operation, structural stresses arise that may lead to deformation, the elimination of which is neither simple nor inexpensive.

For this reason, materials with good vibration damping properties [3] are being sought for use in lathe foundations or as the structural components of such equipment. As noted by Orak in [4], polymer and polymer concrete manufacturing technologies enable the formation of closed structures. Polymer concretes allow the use of closed structures with thicker walls, resulting in higher resonance frequencies [5].

Additionally, the use of polymer matrices from the elastomer group in polymer concrete production (polymer combined with ceramic aggregate) provides improved damping performance in the final structure.

This paper presents such materials, namely polymer concretes based on epoxy resin developed by the authors. The innovative aspect of the material lies in the use of post-consumer waste as part of the filler, specifically garnet originating from waterjet cutting processes. The authors aimed to evaluate the properties of the resulting composite and propose applications for this waste material in accordance with circular economy principles.

2. Research material and methods

Polymer concretes were produced by introducing a polymer binder—synthetic epoxy resin—into a pre-designed aggregate mixture subjected to particle size segregation in accordance with the assumptions presented in the work of Czarnecki [6]. The applied grading curve was selected to ensure a maximum packing density and minimization of intergranular voids, which is critical for achieving high mechanical strength and reduced resin demand. The aggregate segregation process is shown in Figure 1.

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Fig. 1. Aggregate segregation

The aggregate mixture consisted of natural mineral aggregates with a controlled grain size distribution in the range of 0–18 mm, characterized by angular grain morphology and high surface roughness, promoting mechanical interlocking with the polymer matrix. The grading composition of the aggregate mixture was as follows: 50% by weight of fraction No. 1 (0–2 mm), 20% by weight of fraction No. 2 (2–8 mm), and 15% by weight of fraction No. 3 (up to 18 mm). Additionally, the mixture included 5% by weight of post-use garnet abrasive originating from the waterjet cutting process, introduced as a partial replacement of the finest fraction (0–2 mm). The garnet fraction was characterized by high hardness (≈7.5–8 on the Mohs scale), an irregular particle geometry, and residual surface contamination, which may influence interfacial adhesion.

The employed polymer binder was a two-component epoxy resin system based on Epidian 5 and PAC curing agent. The curing system was prepared using a mass ratio of 100:70 (resin:hardener), ensuring an appropriate cross-linking density and mechanical performance. The total polymer content in the composite was maintained at 15% by weight, ensuring effective wetting of the aggregate grains while limiting an excess polymer phase.

The polymer concretes were manufactured by means of a mechanical mixing method under controlled conditions: mixer rotational speed of 350 rpm, ambient temperature of 21°C, and relative humidity of approximately 65%. The total mixing time was 30 minutes, including initial dry mixing of the aggregates (approximately 10 minutes), followed by gradual addition of the epoxy resin system (approximately 10 minutes) and final homogenization (approximately 10 minutes). The mixing process was carried out until uniform distribution of the polymer phase and complete coating of the aggregate particles was achieved.

After mixing, the fresh composite was poured into molds and subjected to vibration compaction in order to eliminate entrapped air and improve structural tightness. The curing process was conducted under laboratory

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conditions (21°C, 65% RH) for 7 days, allowing sufficient polymer cross-linking and stabilization of the mechanical properties.

A view of the produced polymer concretes is shown in Figure 2.

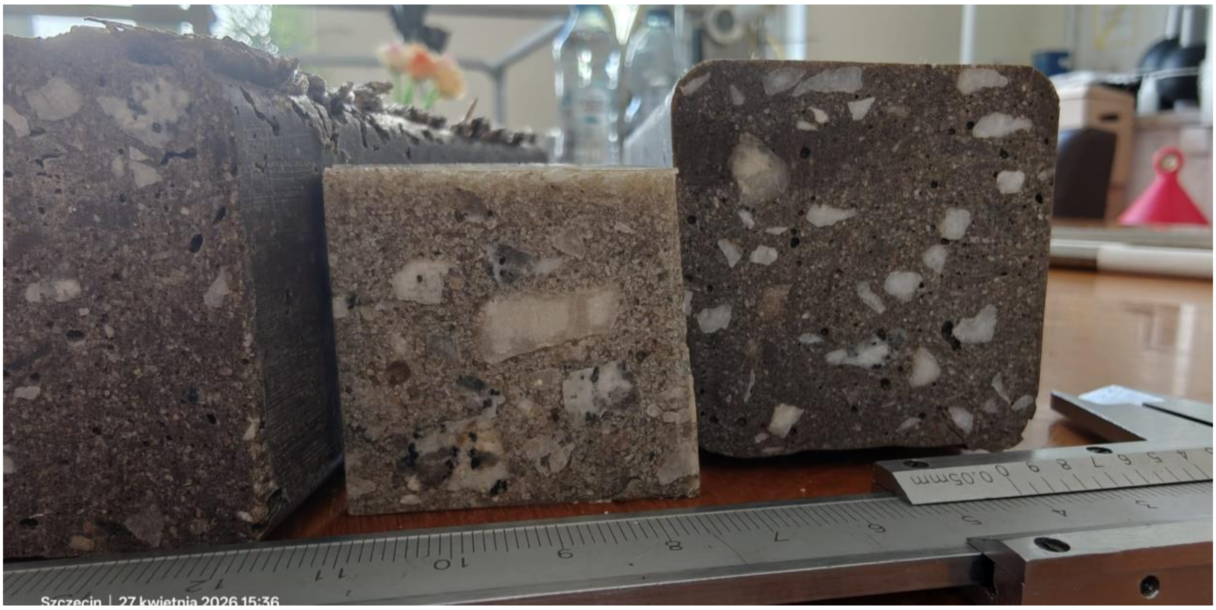

Fig. 2. View of manufactured polymer concretes

Selected properties of the manufactured polymer concretes were tested, including density, flexural strength, compressive strength, Young's modulus, and the logarithmic decrement of damping. The tests were carried out in accordance with relevant European standards, including PN-EN 12390-5:2019 for flexural strength, PN-EN 12390-3:2019 for compressive strength, and PN-EN ISO 1183-1:2026 for density. The damping properties, expressed as the logarithmic decrement, were determined based on the dynamic testing procedures described in ASTM E756 or equivalent methodologies. The tests were performed utilizing equipment available at the Department of Materials Manufacturing Technology and Techniques, Faculty of Mechanical Engineering, Maritime University of Szczecin.

3. Evaluation of selected properties of polymer concretes in comparison with cast irons used in machine tools

Selected properties of cast iron and the polymer concretes are presented in Table 1.

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Table 1. Selected properties of cast iron and polymer concrete based on [7]

Selected properties	Grey cast iron	Polymer concrete	Polymer concrete with post-use garnet
Density g/cm^3	7.4	2.1÷ 2.4	2.2÷ 2.5
Flexural strength N$/mm^2$	150÷ 400	25÷ 40	28÷ 44
Compressive strength N$/mm^2$	350÷ 450	140÷ 170	180÷240
Logarithmic damping decrement	0.003	0.02÷0.03	0.02÷0.04

The observed increase in compressive strength in the composites containing garnet (180–240 MPa), compared to the reference polymer concrete (140 MPa), can be attributed to several interacting mechanisms. First and foremost, the high hardness and stiffness of the garnet particles lead to enhanced local resistance to plastic deformation in stress concentration zones. In addition, the irregular geometry of the particles promotes a more efficient load transfer through mechanical interlocking with the matrix. At the same time, the presence of fine particles may improve structural packing, reducing porosity and increasing the effective interfacial contact area between phases [8].

The strength properties of grey cast iron are significantly more favorable than those of polymer concretes, which makes it necessary to determine Young’s modulus in order to achieve greater structural stability of machines and equipment. Young’s modulus is a characteristic parameter of a given material that describes how the material deforms under the action of applied forces. Therefore, it is an important indicator in the assessment of vibration damping properties.

This parameter defines the stiffness of a material. The higher the Young’s modulus, the stiffer the material, and consequently, the smaller the deformation resulting from forces acting on the object. In anisotropic materials, the value of Young’s modulus varies depending on the direction of the applied force relative to the tested object.

The practical application of Young’s modulus is crucial at the engineering design stage. For example, one of the objectives when designing a structural component of a mechanical device may be to minimize elastic deformation as much as possible. This means that Young’s modulus is a key parameter to be considered during material selection.

The study showed that Young’s modulus was:

- 110 kN/mm² for grey cast iron
- 37 kN/mm² for the manufactured polymer concrete
- 42 kN/mm² for the manufactured polymer concrete with post-use garnet

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The lower value of Young's modulus for polymer concrete results directly from the presence of a viscoelastic polymer phase, whose elastic modulus is orders of magnitude lower than that of metallic phases. The introduction of garnet as a rigid phase may locally increase the effective modulus of the composite; however, at a low volume fraction (5%), this effect remains limited and does not compensate for the dominant influence of the epoxy matrix.

Since Young's modulus is significantly lower for polymer concrete than for cast iron, it is necessary to ensure adequate "static structural stiffness" in structures made from polymer concrete materials. This can be achieved by selecting and designing appropriate wall thicknesses for structural profiles during the design process [9].

Figure 3 presents example beam cross-sections with identical stiffness for grey cast iron and polymer concrete [10]. Nevertheless, because of their structural characteristics, polymer concretes are particularly suitable as filling materials for machine and equipment profiles, especially in machine tools.

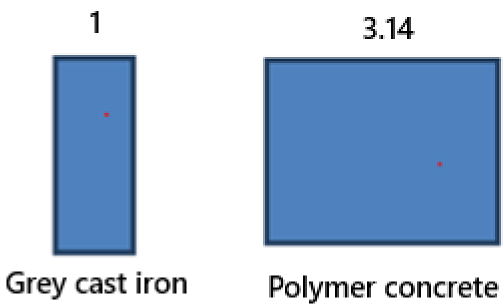

Fig. 3. Comparison of beam cross-sections with identical stiffness for grey cast iron and polymer concrete, shown in centimeters [10]

According to Table 1, considering the logarithmic damping decrement, it can be concluded that the vibration damping in polymer concretes is approximately nine times greater than in cast iron. This is illustrated in Figure 4, which presents the amplitude–frequency characteristics of a machine tool bed made of grey cast iron and polymer concrete.

Figure 5 presents a comparison of vibration damping in a lathe made of cast iron and one containing polymer concrete used as a profile filler, both subjected to impact excitation. After the same elapsed time, vibrations in the polymer concrete component are no longer present (they have been damped out), whereas the vibrations in the cast iron component remain at a high level.

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This demonstrates that polymer concretes can serve as structural filling materials or foundation materials for machine tools, effectively suppressing harmful vibrations that are undesirable from the perspective of the machining process and the workpiece being processed by the lathe.

From the perspective of materials physics, the vibration damping capacity of polymer concrete arises from its complex, multiphase structure. The presence of a viscoelastic polymer matrix enables the dissipation of mechanical energy through internal friction and the relaxation of polymer chain segments [11,12]. In addition, the numerous phase interfaces between the aggregate particles and the matrix act as sites for the scattering of elastic waves, leading to a significant increase in damping compared to homogeneous materials such as cast iron.

The incorporation of garnet into the composite structure influences the damping properties in a complex manner. On the one hand, the increased number of phase interfaces promotes the dissipation of vibrational energy. On the other hand, the high stiffness of the garnet particles may locally restrict the viscoelastic deformation of the matrix, potentially reducing the material's ability to dissipate energy. The overall effect is therefore governed by a balance between these competing mechanisms, which is reflected in the observed range of damping decrement values (0.02–0.04).

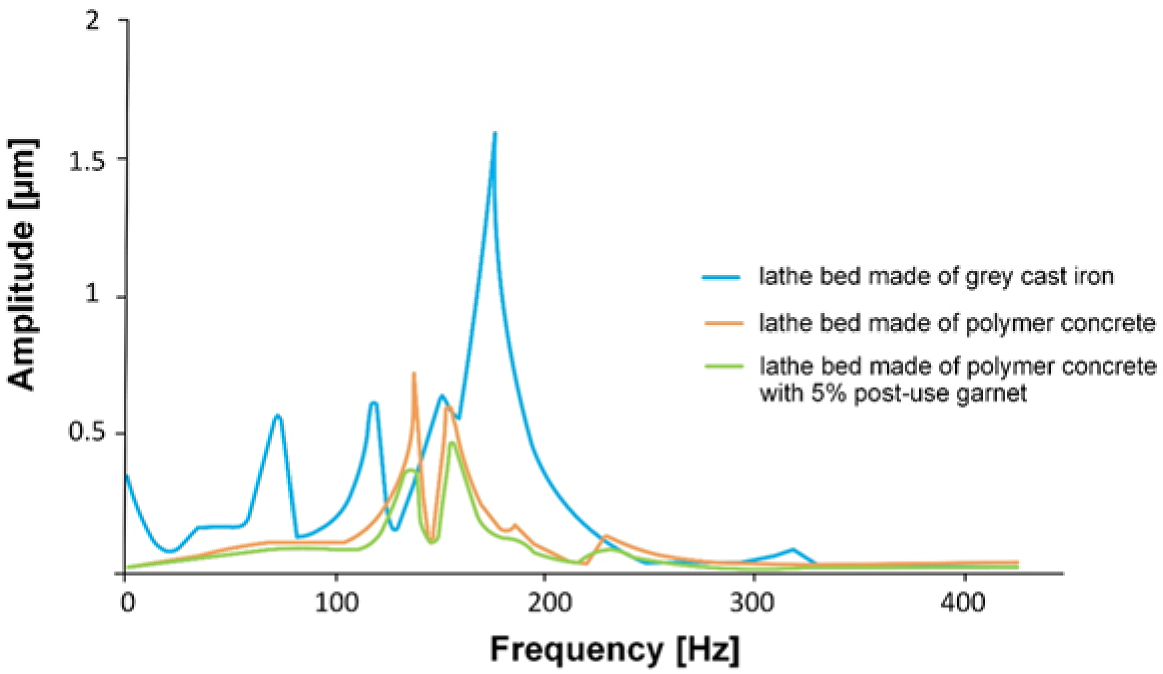

Fig. 4. Amplitude–frequency characteristics of lathe bed made of grey cast iron and polymer concrete, authors' own elaboration based on [10]

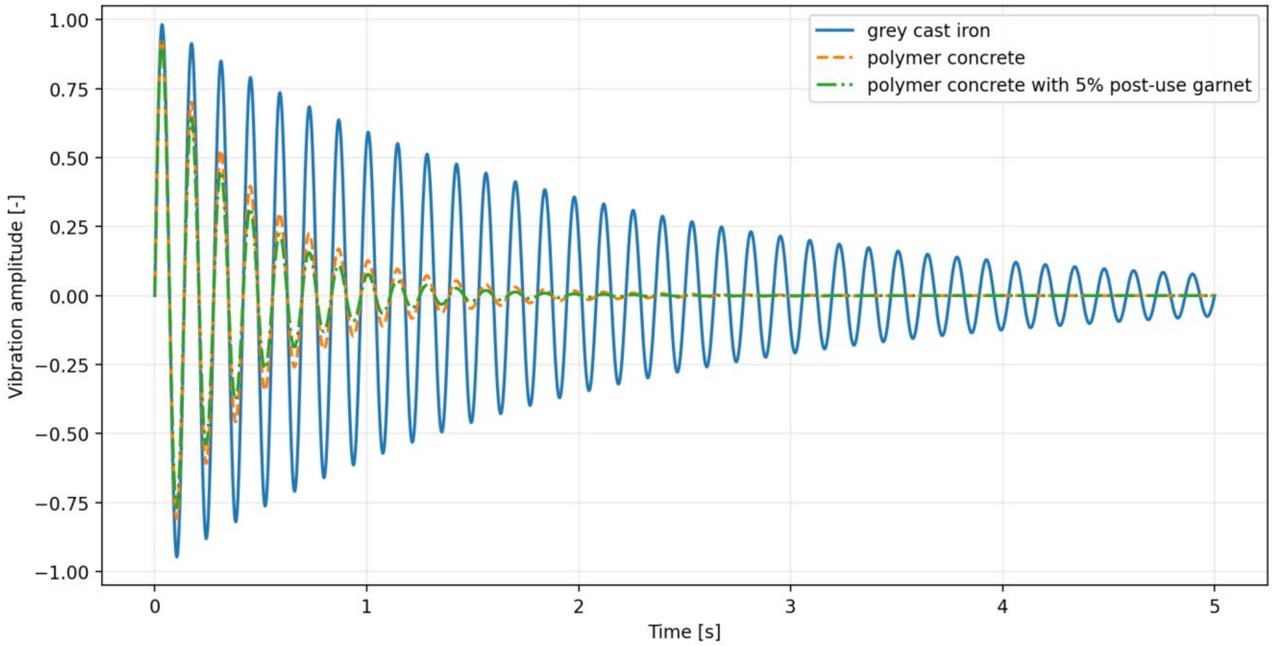

Fig. 5. Visual interpretation of vibration damping in lathe bed made of grey cast iron and polymer concrete in response to a single forced impact used to assess degree of vibration damping.

Conclusions

The evaluation of the damping properties of the manufactured polymer concretes containing a recycled fraction was carried out in this study based on a comparison of the Young's modulus of these materials with that of grey cast iron. The following conclusions were drawn:

- It is possible to produce innovative polymer concretes based on epoxy resin, incorporating aggregates of various gradations and a recycled garnet phase. The introduction of waste garnet as a fine-grained component not only enables the effective utilization of industrial by-products but also leads to enhancement of the composite's mechanical properties, in particular an increase in the compressive strength and potential optimization of the particle packing structure.
- The production of such materials enables at least partial utilization of post-use waste materials.
- These materials may be suitable for filling structural profiles in machine tools, despite the fact that the Young's modulus is nearly three times lower than that of grey cast iron (cast iron: 110 kN/mm², polymer concrete: 37 kN/mm², polymer concrete with post-use garnet: 42 kN/mm²).

The very good damping properties of the polymer concrete in comparison with grey cast iron are confirmed by the value of the logarithmic damping decrement (see Table 1 and Figure 5). The logarithmic decrement of vibration damping is used as a parameter to characterize damping efficiency.

The logarithmic decrement is calculated using the natural logarithm of the ratio between two successive vibration amplitudes. It is equal to the product of the damping coefficient and the vibration period.

This suggests that the manufactured polymer concretes may serve as structural materials capable of replacing cast iron in the design and construction of machines and equipment, particularly those composed of individual modules exposed to vibration during operation.

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