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STEPGRAD
СТЕПГРАД

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EXPERIMENTAL INVESTIGATION OF SUSTAINABLE CONCRETE WITH WASTE PVC SAWDUST AND METAKAOLIN

Abstract:
Concrete is widely used, but its production consumes natural resources and generates significant CO_2 emissions. Modern construction requires structural stability and durability while reducing environmental impact through sustainable materials. This study investigated the use of PVC sawdust as a partial replacement for fine aggregate and metakaolin as a partial replacement for cement in concrete mixtures. The addition of PVC sawdust significantly reduced workability (slump decrease of 96.7 %) and compressive strength (30.2 %), while slightly increasing ductility. Concrete with 15 % PVC sawdust is not suitable for load-bearing elements but may be used in lightweight and non-structural components, supporting waste utilization and sustainable construction.

Keywords: PVC sawdust, metakaolin, fresh concrete properties, mechanical properties

ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ ОДРЖИВОГ БЕТОНА СА ОТПАДНОМ ПВЦ ПИЉЕВИНОМ И МЕТАКАОЛИНОМ

Сажетак:
Бетон је у широкој употреби, али његова производња захтијева значајне количине природних ресурса и узрокује знатне емисије CO_2. Савремена грађевинска пракса захтијева конструктивну стабилност и трајност, уз истовремено смањење утицаја на животну средину кроз примјену одрживих материјала. У овом раду истражена је примјена ПВЦ пиљевине као дјеломичне замјене за ситни агрегат и метакаолина као дјеломичне замјене за цемент у бетонским мјешавинама. Додатак ПВЦ пиљевине значајно је смањио обрадљивост свјежег бетона (смањење слијегања од 96,7 %) и чврстоћу на притисак (30,2 %), уз благо повећање дуктилности. Бетон са 15 % ПВЦ пиљевине није погодан за носеће елементе, али се може примијенити у лаким и неконструктивним елементима, чиме се доприноси употреби индустријског отпада и принципима одрживе градње.

Кључне ријечи: ПВЦ пиљевина, метакаолин, својства свјежег бетона, механичка својства

1. INTRODUCTION

Concrete plays a vital role in the modern construction industry due to its high strength and durability, versatility in shaping, low maintenance requirements, resistance to fire, weather, and earthquakes. In addition, concrete is recyclable, which further contributes to its widespread use. Despite these advantages, its extensive use presents significant challenges in the context of sustainable development and environmental protection. The production of concrete requires large amounts of natural resources and energy, while also generating considerable CO_2 emissions that contribute to environmental degradation.

Aggregates constitute approximately three-quarters of the total volume of concrete and strongly influence the properties of both fresh and hardened concrete. The growing demand for concrete has resulted in intensive exploitation of natural aggregates. This excessive extraction causes serious environmental problems, including soil erosion, alteration of river courses, air pollution, and the destruction of natural habitats. Moreover, aggregate extraction processes often involve heavy machinery and blasting operations, which generate noise, vibrations, and dust, negatively affecting both ecosystems and human health. To address these issues, researchers have increasingly focused on the development of sustainable alternatives by incorporating waste materials into concrete mixtures. Various waste materials such as recycled aggregates from demolished concrete, plastic waste, glass, rubber, and bio-waste have been investigated for their potential use in concrete production. The incorporation of such materials can reduce the consumption of natural resources, decrease waste generation and contribute to more sustainable construction practices. As a sustainable alternative, the researchers proposed replacing 10 % of fine sand volume in structural concrete with processed waste plastic, resulting in concrete with nearly the same strength as the reference mix [1]. This approach could save 820 million tons of sand annually and reduce plastic waste on streets.

Plastic waste represents a particularly serious environmental problem due to its slow decomposition and harmful effects on ecosystems. Large quantities of plastic products are discarded in landfills or the natural environment [2], [3]. Incorporating plastic into concrete mixtures provides an opportunity to recycle waste materials while reducing the demand for natural aggregates [4], [5]. Previous studies have shown that the use of plastic waste as a partial replacement for aggregates can influence the properties of concrete. For example, in the case presented by [6], the compressive strength decreased from 33 MPa to approximately 26 MPa with 15 % PVC plastic waste by partial replacement of coarse aggregate. Similar observations were reported in [7] for different types of plastic waste incorporated into the concrete. Moreover, studies have shown that plastic granules, due to their hydrophobic nature and poor adhesion to the cement matrix, can lead to increased porosity and microcracking over time [8]. The incorporation of waste PVC as a partial fine aggregate replacement was found to decrease mechanical performance of mortar while enhancing sustainability at low replacement levels [9]. The consumption of PVC products in the building and construction sector has been steadily increasing. However, only a limited number of studies have investigated the use of PVC waste in cement-based composites. A brief review of the potential application of PVC plastic as an aggregate in cement composites was reported in [10]. Nevertheless, plastic-modified concrete may offer advantages such as improved flexibility, enhanced impact resistance, and reduced structural weight. The workability of concrete mixtures is another important parameter affecting the quality of the final product and its placement. Several studies indicate that the addition of recycled plastic reduces concrete workability, particularly at higher replacement levels [1], [10]. Due to the lower density of plastic compared to natural aggregates, concrete containing plastic typically has a lower overall density [11], [12].

In addition to replacing aggregates, reducing the cement content in concrete is another important approach for minimizing environmental impact. Cement production is responsible for a significant portion of global CO_2 emissions. Therefore, supplementary cementitious materials (SCMs) are widely used to partially replace Portland cement in concrete mixtures [13]. Among various SCMs such as fly ash, silica fume, and ground granulated blast furnace slag, metakaolin has attracted considerable attention due to its high pozzolanic activity and beneficial effects on concrete properties. Metakaolin is an environmentally friendly pozzolanic material obtained by calcining kaolinite clay at temperatures between 650 and 750 °C. Due to its high content of reactive silica and alumina, metakaolin reacts with calcium hydroxide ($Ca(OH)_2$) released during cement hydration, forming additional calcium silicate hydrate (C–S–H) gel. This reaction improves the microstructure of concrete and enhances its mechanical strength and durability [14]. However, high replacement levels may reduce workability, requiring careful mix design [15]. Additionally, it improves the cohesion of fresh concrete while reducing bleeding and aggregate segregation. Several papers suggest that low mechanical properties of concrete containing plastic aggregate can be improved with SCMs. Punitha et al. [16] reported that inclusion of 10 % metakaolin and 15 % HDPE plastic improved the strength of concrete.

Despite numerous studies investigating recycled plastic aggregates and supplementary cementitious materials separately, limited research has examined the combined use of plastic waste and metakaolin in concrete mixtures. To the best of the authors' knowledge, the combined effect of PVC aggregate and metakaolin on the fresh and hardened properties of concrete has not yet been extensively reported in the literature.

Therefore, the aim of this study is to investigate the influence of PVC sawdust as a partial replacement for fine aggregate and metakaolin as a partial replacement for cement on the properties of concrete. The experimental program involved the preparation and testing of two concrete mixtures. The reference mixture contained 10 % metakaolin as a cement replacement, while in the second mixture 15 % of the fine aggregate volume was replaced with PVC sawdust. The properties of fresh concrete, including workability, density and porosity were evaluated, while the hardened concrete was tested for compressive strength, flexural tensile strength, splitting tensile strength and water penetration resistance. These parameters are essential for assessing the potential application of such sustainable concrete mixtures in construction practice.

2. CONCRETE MIXING AND SPECIMEN PREPARATION

The experimental study was conducted in the Laboratory for materials at the Faculty of Civil Engineering, University of Rijeka, Croatia. To investigate the combined effects of metakaolin and PVC sawdust on the fresh and hardened properties of concrete, two concrete mixtures were prepared. Both mixtures contained the same mass percentage of metakaolin, while one mixture additionally included PVC sawdust.

Tests on fresh concrete were performed immediately after mixing to determine temperature, workability (consistency measured by the slump test), density (bulk density) and air content. For each concrete mixture, three prisms (100 mm × 100 mm × 400 mm) were cast for flexural strength testing, and six cubes with 150 mm edges from which three were used for compressive strength testing, while the remaining three were used for splitting tensile strength and water penetration tests. The results were compared to evaluate the combined effects of metakaolin and PVC sawdust on the properties of both fresh and hardened concrete.

2.1. MATERIALS

In the experimental part of the study, the following materials were used for the preparation of concrete mixtures: natural aggregate fractions, cement, superplasticizer, water, metakaolin, and PVC sawdust. PVC sawdust was used as a partial replacement for fine aggregate, while metakaolin was applied as a partial replacement for cement.

Crushed limestone aggregate produced by Holcim d.o.o., with a maximum grain size of 16 mm was used in the mixture preparation. The properties of fine and coarse aggregates were found to comply with the requirements of HRN EN 12620 [17]. The density of the aggregate in a saturated surface-dry condition was 2.66 Mg/m^3, while water absorption was 1.3 %, 1.2 %, and 1.1 %, respectively, from the coarsest to the finest fraction. The proportions of individual fractions in the total aggregate composition were 0–4 mm (54 %), 4–8 mm (24 %), and 8–16 mm (22 %). The cumulative particle size distribution curve of natural aggregate is presented in Figure 1. The cumulative grading falls within the limit curves according to the national standard HRN 1128 [18].

PVC sawdust, an industrial waste material obtained during the production of PVC window frames, with an approximate density of 1.0 g/cm^3, was used as a replacement for natural sand. The sieve analysis curves of PVC sawdust and fine aggregate are presented in Figure 2. The particle size distribution curves indicate that the natural fine aggregate 0–4 mm contains a higher content of fine particles compared to PVC sawdust, which exhibits a steeper increase in the percentage passing between the 1 mm and 4 mm sieve sizes suggesting a predominance of medium-sized particles. However, the majority of PVC sawdust particles are smaller than 4 mm, indicating that its particle size range is comparable to that of fine aggregate. Therefore, PVC sawdust can be considered a suitable material for partial replacement of natural sand.

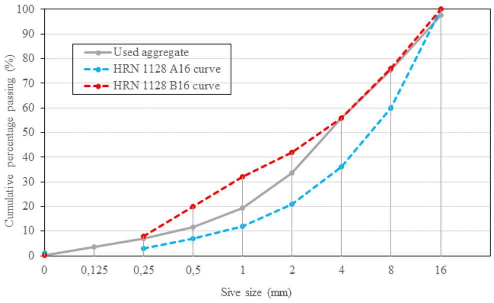


Figure 1. Aggregate particle size distribution curve in line with HRN 1128 limits.

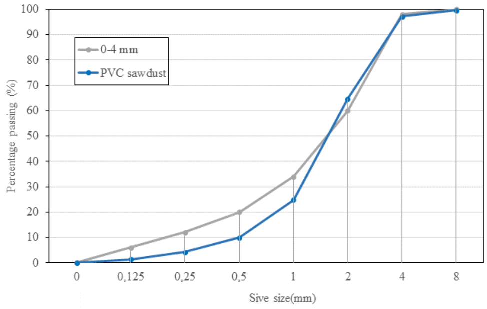
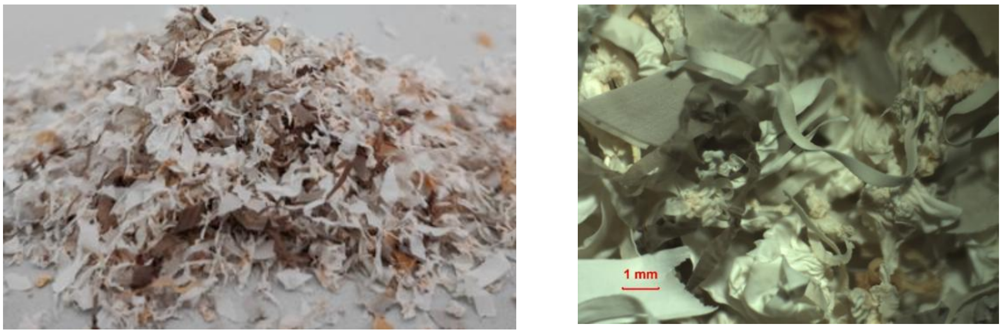


Figure 2. Particle size distribution curve of fine aggregate and PVC sawdust

Figure 3 shows microscope analysis of PVC sawdust. The particle surfaces appear very fine and fibrous, with a mix of smooth and slightly rough edges. The particle shapes are irregular and curly, with a combination of flat strips, spirals, and small crumpled fragments. Overall, it looks like curly, ribbon-like sawdust with a combination of thin strips and small crumpled particles.



(a) (b)

Figure 3. PVC sawdust (a) normal size and (b) at 10 × magnification

Table 1 summarizes the physical and chemical properties of the cement and metakaolin used in the studied mixtures. Blended Portland cement CEM II/B-M (S-V) 42.5 N, supplied by Holcim (Hrvatska) d.o.o., was used as the binder. Its chemical composition and physical properties (Table 1) comply with the requirements of HRN EN 197-1 [19]. Metakaolin Metaver™ M, produced by Newchem, with a density of 2.60 g/cm³, was used as a partial replacement for cement. According to the manufacturer's recommendations, the replacement level of cement with metakaolin ranges from 5 % to 15 % by mass of cement [14]. Alumina in used metakaolin is 41 % which is more when compared to cement so it can act as filler to strengthen the microstructure of concrete and it reduces the volume of pores in cement paste.

Table 1. Physical and chemical properties of used cement and metakaolin

Physical properties (for 1m^3)			Chemical composition (% by mass)		
	Cement	Metakolin		Cement	Metakolin
Initial setting time (min)	194	120	SiO_2	19.31	56.00
Density (kg/m^3)	3000	2600	Al_2O_3	4.31	41.00
Specific surface-Blaine (cm^2/g)	3307	24 000	CaO	61.08	0.30
Particle size distribution μm (d50)	19.45	4.5	MgO	2.38	0.20
			SO_3	2.96	-
			Fe_2O_3	2.28	1.00
			K_20	0.86	0.90

Water from the municipal water supply system was used for the preparation of concrete mixtures. In order to improve the workability of fresh concrete, a chemical admixture, the superplasticizer Dynamon SF 16 S, produced by Mapei d.o.o, with a density of 1.10 g/cm³, was used. It is a universal superplasticizer based on modified acrylic polymers, characterized by excellent slump retention and low viscosity of fresh concrete mixtures. The optimal effect is achieved when the admixture is added after the other components together with at least 80 % of the total mixing water. The recommended dosage ranges from 0.2 % to 2.0 % by mass of cement, while the maximum allowable dosage is 2.5 %.

2.2. MIXTURES

The selection of material proportions in the concrete mixtures was based on available data from the literature as well as on the authors' previous experience gained during earlier studies of cement mixtures incorporating PVC waste sawdust [16, 20].

Two concrete mixtures were prepared: a reference mixture with 10 % cement mass replaced by metakaolin (designated as REF + 10 % M) and a mixture with 10 % cement mass replaced by metakaolin and an additional replacement of 15 % of the volume of fine aggregate with PVC sawdust (designated as REF + 10 % M + 15 % PVC). The designation of each mixture includes information on the replacement levels of metakaolin and PVC sawdust used in the mixture. Table 2 presents the composition of the concrete mixtures, while Figure 5 illustrates the mix design.

Both mixtures were designed with the same effective water-to-cement ratio of 0.5. The quantities of powder materials were kept constant: 369 kg/m³ of cement and 41 kg/m³ of metakaolin. The same amount of superplasticizer was initially applied in both mixtures (0.5 % by mass of cement and metakaolin), with the aim of achieving fresh concrete consistency corresponding to slump class S3. However, due to the low workability of the mixture containing PVC sawdust, the REF + 10 % M + 15 % PVC mixture required an additional amount of superplasticizer (2 % by mass of cement and metakaolin), compared to the reference mixture to improve workability. Therefore, the maximum recommended dosage of 2.5 % by mass of binder was applied. The main objective was to determine whether a superplasticizer could improve the workability and homogeneity of mixes containing PVC sawdust.

Table 2. Composition of mixtures (kg/m³)

Mixture	REF + 10 % M	REF + 10 % M + 15 % PVC
Cement	369	369
Metakaolin	41	41
Water	205	205
Water - -cement	0.5	0.5
Superplasticizer (0.5 %)	2.05	2.05 (+8.2)
0-4 mm aggregates	917.1	842.8
4-8 mm aggregates	407.6	407.6
8-16 mm aggregates	373.6	373.6
PVC aggregates	-	51.7

(a)

(b)

Figure 4. Fractured surface of hardened concrete specimens (a) without PVC sawdust and (b) with 15 % PVC sawdust

Before the preparation of the concrete mixtures, the masses of the components were corrected according to the actual moisture content of the aggregate in the laboratory. Afterward, all ingredients were precisely weighed and added to the mixer according to a predefined sequence. First, the dry materials (aggregate, cement, metakaolin, and PVC sawdust) were placed in the mixer and mixed for approximately two minutes. Then, 80 % of the total amount of water was added, and mixing continued for an additional two minutes. Finally, the remaining 20 % of water with the previously dissolved superplasticizer was added, and mixing was continued for another two minutes.

For the mixture REF + 10 % M + 15 % PVC, in which additional superplasticizer was required, it was directly added to the mixer after the initial mixing process of the all components. In such cases, after adding the superplasticizer to the fresh mixture, mixing was continued for an additional 120 seconds until a homogeneous mixture was obtained.

After mixing in the laboratory mixer, the fresh concrete was tested and cast into molds for the determination of hardened concrete properties. In order to ensure proper compaction of the mixture and the removal of entrapped air, all specimens were vibrated on a vibrating table. More detail information about concrete mixing and specimen preparation can be found in [21].

3. TESTING AND PROPERTIES OF FRESH CONCRETE

After the preparation of the concrete mixtures, tests on fresh concrete were performed. The fresh concrete testing program included the determination of consistency by the slump test method, density (bulk density) of the fresh mixture and air content. In addition, the temperature of the fresh concrete was also measured immediately after the mixing process was completed. The results of the fresh concrete tests are presented in Table 3.

Table 3. Results of testing fresh concrete

Mixture	REF + 10 % M	REF + 10 % M + 15 % PVC
Temperature (°C)	24.0	21.6
Slump value (mm)	90	3
Density (kg/m^3)	2360	2140
Porosity (%)	2.70	7.60

3.1. WORKABILITY (CONSISTENCY)

The consistency of fresh concrete was determined using the slump test with an Abrams cone, in accordance with HRN EN 12350-2 [22], in order to assess the workability of the fresh concrete mixture. The slump height was measured relative to the cone (Figure 6), and the consistency class was determined according to HRN EN 206 [23].

(a) (b)

Figure 5. Slump test of the concrete mixture (a) without PVC sawdust and (b) with 15 % PVC sawdust

In the conducted tests, the reference concrete mixture exhibited a slump of 90 mm (slump class S3), whereas the mixture containing PVC sawdust showed significantly reduced workability, with a slump of only 3 mm (slump class S1). According to literature data, the incorporation of PVC sawdust often leads to a substantial reduction in workability, sometimes resulting in a nearly unworkable mixture [12]. This can be attributed to the particle size distribution of PVC sawdust with lower amount of fine particle (< 0,5 mm). The obtained results thus confirm the general trend of significant workability reduction due to the addition of PVC sawdust.

To achieve the target workability in the mixture containing PVC sawdust, the superplasticizer was added gradually in 0.5 % step increments, up to the recommended maximum dosage of 2.5 % by mass of binders. However, the addition of the superplasticizer did not result in any significant increase in slump. The results indicate that even at the maximum dosage, the concrete mixture with 15 % PVC sawdust did not achieve satisfactory workability. The slump remained within class S1, and visual observations revealed segregation of mixture components, indicating insufficient cohesion and homogeneity of the fresh concrete, more porous structure, as well as poor contact between the cement paste and PVC sawdust (Figure 7). This behavior can be attributed to the specific properties of PVC sawdust. The waste aggregate in the form of PVC sawdust does not absorb water, and therefore does not contribute to the formation of a strong bond with the cement paste. Additionally, the smooth surface of PVC particles adversely affects the adhesion between the sawdust, cement paste, and natural aggregate, resulting in reduced slump, lower compactness, and weakened cohesion of the concrete mixture. Moreover, the irregular and elongated shape of PVC particles negatively influences workability due to the increased specific surface area.

Figure 6. Fresh concrete mixture with 15 % PVC sawdust showing very low workability, visible segregation, and poor cohesion of components

3.2. DENSITY

Cube shaped specimens prepared for compressive strength testing were used to measure the density of fresh concrete. The density, or bulk density, was determined as the ratio of its mass to the volume it occupies when compacted in moulds, in accordance with the procedure specified in the HRN EN standard [12]. In the conducted experiment, the reference concrete mix achieved a density of 2360 kg/m³, while the mix with 15 % of PVC sawdust exhibited a lower density of 2140 kg/m³ (Table 3).

According to the literature, concrete mixes incorporating PVC sawdust generally have lower densities compared to conventional concrete mixes [12]. The obtained results confirm this trend, with the PVC sawdust mix in this study showing a decrease in the density of fresh concrete by approximately 9.3 % compared to the reference mix. The reduction in density is due to the significantly lower density of PVC sawdust compared to the natural aggregate it partially replaces. Additionally, the shape of PVC sawdust prevents a more compact packing of the materials and increases the proportion of entrapped air in the mix (Figure 8).

Figure 7. Compacted fresh concrete

3.3. AIR CONTENT

The air content of fresh concrete was determined in accordance with the HRN EN 12350-7 standard [24]. The test results showed that the reference concrete mix contained 2.7 % air, whereas the mix with 15 % of PVC sawdust exhibited a significantly higher air content of 7.6 % (Table 3). The results clearly indicate that the incorporation of PVC sawdust substantially increases the amount of entrapped air in the concrete mix (Figure 8), with the air content being almost three times higher than in the reference mix. The higher air content can be mainly attributed to the coarser particle size, irregular shape, and surface characteristics of the PVC sawdust, which prevent dense packing of the mixture and enhance the entrapment of air in fresh concrete.

Such an increase in air content can have a significant impact on the properties of hardened concrete. A reduction in compressive strength and density, as well as increased permeability, is expected.

4. TESTING AND PROPERTIES OF HARDENED CONCRETE

After curing the concrete specimens in water for 28 days, tests were conducted to evaluate the properties of hardened concrete. The testing program included the determination of compressive strength, flexural and splitting tensile strength, density of hardened concrete, and water penetration under pressure. Each result was obtained as the average of three (3) specimens of the same mix.

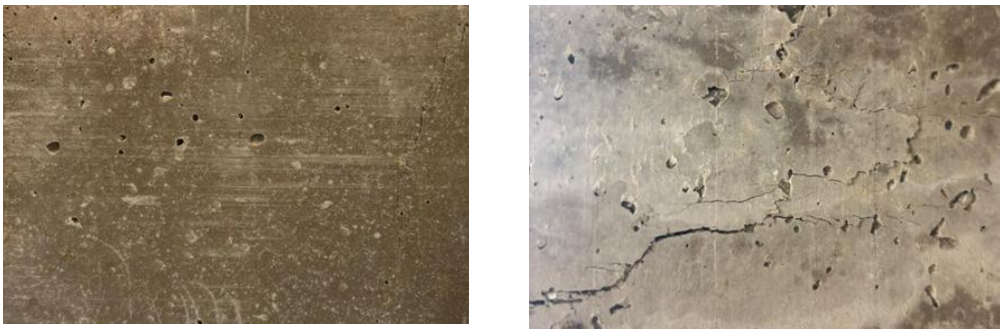
4.1. DENSITY

Before testing compressive strength, the cube specimens were weighed, and their dimensions were measured to determine the density (bulk density) of hardened concrete. Three (3) specimens were tested for each mix. Table 4 presents the results for individual cubes (C1, C2, and C3) as well as the mean density for each mix. The density of hardened concrete was calculated as the mean value of the three specimens of the same mix. The reference mix exhibited a density of 2304 kg/m^3, while the mix containing 15 % of PVC sawdust showed a lower density of 2112 kg/m^3, representing a reduction of approximately 8.3 % compared to the reference mix.

Table 4. Density of studied concrete mixtures in hardened state

Mixture	Sample	Density (kg/m^3)		increase/ decrease
		Individual value	Mean value	
REF + 10 % M	C1	2301	2304	-
	C2	2308		
	C3	2304		
REF + 10 % M + 15 % PVC	C1	2078	2112	-8.3
	C2	2138		
	C3	2122		

The reduction in density is due to the significantly lower density of PVC sawdust compared to the natural aggregate it partially replaces, as well as an increased air content. These density differences are also reflected in the structure of the concrete. In Figure 9, which shows the outer structure, increased porosity is clearly visible in the specimens containing PVC sawdust, further confirming the measured density values.



(a) (b)

Figure 8. Outer structure of the concrete mixture (a) without PVC sawdust and (b) with 15 % PVC sawdust

4.2. COMPRESSIVE STRENGTH

Compressive strength is one of the key properties of hardened concrete. The test was carried out according to the procedure defined in the HRN EN 12390-3 standard [25]. For each specimen, the fracture pattern was visually analyzed, the maximum load at failure was recorded, and the compressive strength was calculated according to the formula provided in HRN EN 12390-3 [25]. Tests were conducted using a hydraulic press with a capacity of 3000 kN.

Table 5 presents the compressive strength values for individual specimens (three specimens per mix) as well as their mean values. The results show a decrease in compressive strength with the addition of PVC sawdust, which aligns with findings reported in the literature [9, 12]. The reference mix achieved a compressive strength of 42.04 MPa, while the mix containing 15 % PVC sawdust exhibited a significantly lower value of 29.35 MPa, representing a reduction of approximately 30 % compared to the reference mix. This decrease can be attributed to the inclusion of PVC sawdust, which reduces workability and increases the porosity of the material.

Table 5. Compressive strength of studied concrete mixtures

Mixture	Sample	Compressive strength (N/mm^2)		increase/ decrease
		Individual value	Mean value	
REF + 10 % M	K1	42.5	42.0	-
	K2	41.4		
	K3	42.3		
REF + 10 % M + 15 % PVC	K1	27.3	29.3	-30.2
	K2	30.7		
	K3	30.0		

4.3. FLEXURAL TENSILE STRENGTH

The flexural tensile strength was determined by applying a two-point load using the displacement-controlled method on prism specimens measuring 100 mm × 100 mm × 400 mm, with a bending testing device with a capacity of 300 kN. The mid-span deflection was measured using LVDT sensors positioned on the front and rear faces of the specimen (Figure 10).

Figure 9. Flexural tensile strength testing using the displacement-controlled method

During testing, the specimens were loaded at a uniform rate of 0.1 μm/s until failure. The increase in applied force and the corresponding deflection were continuously recorded. At the end of the test, the failure load and the mode of fracture were noted. Three specimens were tested for each concrete mix. Table 6 presents a comparison of the individual results for each prism (labeled P1, P2, and P3) and the mean flexural tensile strength obtained for each mix.

Table 6. Flexural tensile strength of studied concrete mixtures

Mixture	Sample	Flexural strength (N/mm^2)		increase / decrease
		Individual value	Mean value	
REF + 10 % M	P1	3.3	3.4	-
	P2	3.4		
	P3	3.6		
REF + 10 % M + 15 % PVC	P1	3.4	3.6	4.1
	P2	3.7		
	P3	3.6		

The results indicate a slight increase in flexural tensile strength with the addition of PVC sawdust. The reference mix achieved a flexural tensile strength of 3.4 MPa, while the mix containing 15 % PVC sawdust reached a slightly higher value of 3.6 MPa, representing an increase of approximately 4.1 % compared to the reference mix. According to the literature, the inclusion of PVC sawdust can positively influence the tensile properties of concrete due to the increased ductility of the material. The load–deflection diagram (Figure 10) shows that the addition of 15 % PVC sawdust results in greater deflection after the peak load is reached, indicating enhanced ductility of the concrete mix compared to the reference mix.

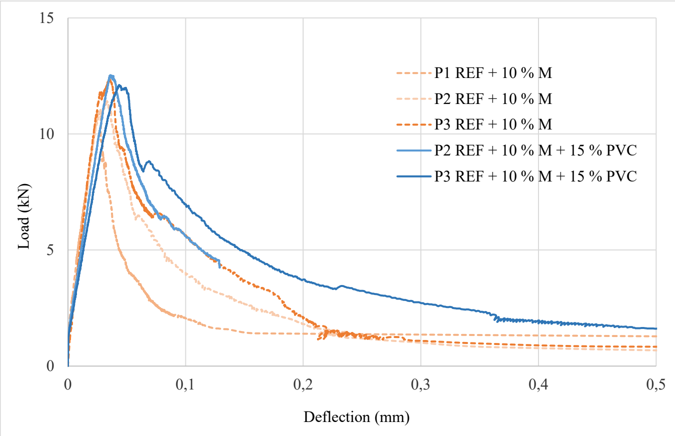
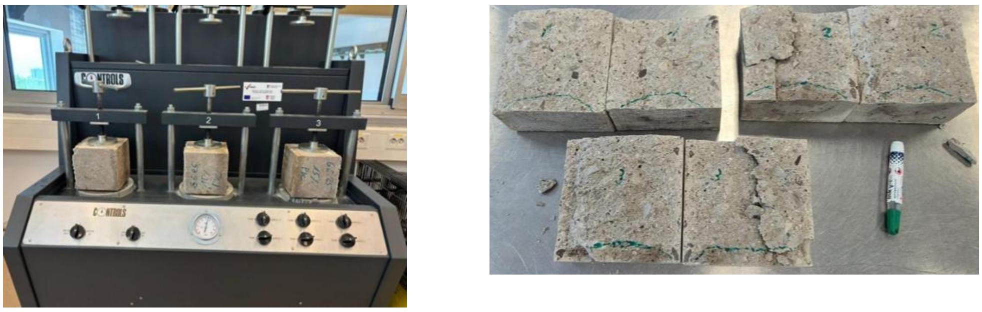


Figure 10. Load deflection curves of studied concrete mixtures

4.4. WATER PENETRATION DEPTH UNDER PRESSURE

The water penetration depth under pressure was determined in accordance with the HRN EN 12390-8 standard [26]. Concrete cube specimens with edge lengths of 150 mm were used as test samples. After 28 days of curing in water at 20 ± 2 °C, the specimens were placed in a water penetration testing device (Figure 12a). After 72 hours of exposure to water under pressure, the specimens were removed from the device and split vertically in a press, perpendicular to the surface exposed to water. The water penetration front was marked on the cross-section of each specimen using a marker (Figure 12b), and the penetration depth was determined by measuring the maximum visible depth of water ingress, expressed in millimeter. The results for individual specimens (C4, C5, and C6), along with the mean maximum water penetration depth for each mix, are presented in Table 7.



(a) (b)

Figure 11. (a) The water penetration testing device and (b) measuring water penetration depth

The results show that the reference mix achieved a mean water penetration depth of 22 mm, while the mix containing 15 % PVC sawdust exhibited a higher mean depth of 28.3 mm, representing an increase of approximately 28.8 % compared to the reference mix. These findings indicate a decrease in the water impermeability of concrete containing PVC sawdust, which contradicts the results reported by [12]. This behavior can be attributed to increased porosity and reduced compactness of the concrete structure, allowing water to penetrate more easily into the material. The higher pore content and weaker adhesion between the cement paste and PVC sawdust contribute to the formation of capillary pores through which water penetrates deeper into the concrete structure [11].

Table 7. Measured water penetration depth of studied concrete mixtures

Mixture	Sample	Maximum depth of water penetration (mm)		increase / decrease
		Individual value	Mean value	
REF + 10 % M	C4	22.0	22.0	-
	C5	24.0		
	C6	20.0		
REF + 10 % M + 15 % PVC	C4	22.0	28.3	28.8
	C5	32.0		
	C6	31.0		

4.5. SPLITTING TENSILE STRENGTH

The method for determining the splitting tensile strength of concrete is defined in the HRN EN 12390-6 standard [27]. Tests were performed on cube specimens that had been previously subjected to water penetration testing. Table 8 presents the results for individual specimens (C4, C5, and C6) and the mean splitting tensile strength for each mix. The results show that the reference mix achieved a splitting tensile strength of 2.78 MPa, while the mix containing 15 % PVC sawdust reached a slightly lower value of 2.63 MPa, representing a reduction of approximately 5.4 % compared to the reference mix. This reduction can be attributed to the properties of PVC sawdust and its weaker bond with the cement paste [9]. The smooth and hydrophobic surface of PVC particles reduces adhesion to the cement matrix, impairing stress transfer in the splitting zone and consequently decreasing the concrete's resistance to tensile stresses [1].

Table 8. Splitting tensile strength of studied concrete mixtures

Mixture	Sample	Split tensile strength (N/mm^2)		increase / decrease
		Individual value	Mean value	
REF + 10 % M	C4	2.7	2.8	-
	C5	2.8		
	C6	2.8		
REF + 10 % M + 15 % PVC	C4	2.4	2.6	-5.4
	C5	2.5		
	C6	3.0		

5. SUMMARY AND CONCLUSIONS

The main objective of this study was to investigate the combined effect of alternative materials, PVC sawdust derived from the production of windows and frames as a partial replacement for fine aggregate, and metakaolin as a partial replacement for cement, on the properties of fresh and hardened concrete. Special attention was given to the role of a superplasticizer in improving workability and mixture homogeneity, thereby ensuring satisfactory performance of the concrete mixtures.

In the experimental program, two concrete mixes were prepared. The first mix served as the reference, incorporating 10 % cement replacement with metakaolin, while the second mix contained the same proportion of metakaolin and an additional 15 % replacement of fine aggregate with PVC sawdust. The results of the two mixes were compared. Overall, partial replacement of fine aggregate with PVC sawdust increases the porosity of concrete and consequently reduces its density, mechanical and durability properties.

Slump tests indicated that the reference mix achieved a slump of 90 mm. The mix containing 15 % PVC sawdust exhibited an almost complete loss of workability, with a slump of only 3 mm, corresponding to a reduction of approximately 96.7 % compared to the reference mix. This confirms the general trend of reduced workability with the inclusion of PVC sawdust, primarily due to poor adhesion between the cement paste and PVC particles.

Gradual increases in the superplasticizer dosage up to the maximum recommended level did not result in significant improvements in workability. The slump remained in class S1, and the mixture components appeared separated, indicating insufficient cohesion, poor homogeneity, and weak contact between the cement paste and PVC sawdust.

Density measurements showed that the reference mix had a fresh concrete density of 2360 kg/m^3, whereas the mix with 15 % PVC sawdust reached 2140 kg/m^3, representing a reduction of approximately 9.3 %. These results are consistent with literature values and confirm that the inclusion of PVC sawdust reduces both the density and homogeneity of the mixture.

Mechanical testing revealed that the addition of 15 % PVC sawdust significantly reduced compressive strength, from 42.04 MPa in the reference mix to 29.35 MPa, corresponding to a 30.2 % decrease. On the other hand, a slight increase in flexural tensile strength was observed, rising from 3.44 MPa to 3.59 MPa, an improvement of 4.1 %, accompanied by behavior that is more ductile. In contrast, splitting tensile strength decreased from 2.78 MPa to 2.63 MPa, representing a reduction of 5.4 %.

Such concrete mixtures may be suitable for applications where high compressive strength and workability are not critical requirements, such as screeds, lightweight concrete elements, and other non-structural applications, including pavements, fences, and decorative concrete elements. In addition, the increased water permeability caused by the incorporation of PVC sawdust may be beneficial for pavement applications that require efficient water drainage.

However, the workability of concrete containing plastic materials requires further investigation. Improving the workability of such mixtures is expected to enhance their mechanical performance. Therefore, the use of different types of chemical admixtures should be further explored.

To conclude, modern construction should focus not only on ensuring the stability and durability of structures but also on reducing environmental impact through the use of sustainable materials. The incorporation of PVC sawdust in concrete contributes to sustainability by enabling the reuse of an industrial by-product that would otherwise end up in landfills.

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