

State-of-the-Art on the Feasibility Assessment of Recycling of Oil Refinery Wastes in Cement Composites with Particular Emphasis on Spent FCC Catalysts

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Abstract

Currently, the significance of oil refinery industry is unquestionable because of the increasing demand for petrochemical products, such as fuels, monomers, and organic chemicals. Despite this, apart from high greenhouse gas emissions, numerous oil and natural gas refining processes are distinctly associated with the generation of a considerable amount of Oil Refinery Wastes (ORWs) in different forms, which need proper disposal and valorization. Nonetheless, at present, solid ORWs are mainly sent to landfills. Such a procedure, apart from high disposal costs, results in significant environmental pollution related to the release of chemical contaminants to soil and water environment. Consequently, these pollutants might poison natural flora and digestive systems of animals, thereby contributing to the general degradation of useful land and a serious health risk. To cope with that issue, ORW recycling in cement-based materials might be considered a reliable course of action, as the hardened concrete is capable to bind contaminants that ORW comprises. This article focuses on actual literature knowledge, limitations, and chances in the scope of a comprehensive approach to sustainable management of ORWs through their utilization in cementitious composites. The special emphasis was placed on presenting the impact provided by the addition of ORWs on the numerous performances of cementitious mixes and hardened concrete. The environmental and economic aspects were also discussed, particularly in the scope of CO₂ emission reductions and cost savings. Finally, the proposal for future tests, including investigating the correlation between valorization of ORWs and toxicity of ORW-blended composites, were proposed.

Keywords: oil refinery waste; chemical properties; mechanical properties; cementitious composites

Academic Editors: Salvatore Verre and Xuanyi Xue

Received: 10 June 2026

Revised: 1 July 2026

Accepted: 17 July 2026

Published: 21 July 2026

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1. Introduction

1.1. General Research Significance

Daily and industrial activities are indisputably associated with the significant amount of CO₂ emissions released to the atmosphere. It is clearly known that CO₂, as a greenhouse gas, contributes to serious environmental impacts, one of the most essential

being global warming and its related issues. To overcome these challenges, the European Green Deal was adopted by the European Union with the aim of achieving climate neutrality by 2050 [1]. Accordingly, the emission allowance prices are increasing constantly, as reported by the EEX, to promote reductions in CO₂ emission coefficient across EU member states [2]. In this regard, industrial sectors which play a crucial role in global CO₂ emission should be identified and developed by implementing various techniques and innovative solutions to achieve emission levels acceptable by European laws and directives. Currently, one of the industries with the greatest environmental impact is the construction sector, which widely uses cementitious composites, i.e., mortars and concretes. This is primarily because the production process of cement, their crucial constituent used as a binder, is based on processing natural resources, consists of limestone decarbonization, and requires high temperatures and considerable electricity effort. Accordingly, each ton of cement consumes approximately 1.500 kg of raw materials [3] and generates emissions of approximately 600–700 kg of CO₂, according to the Association of Cement Producers [4]. Taking into consideration the substantial scale of usage of various cementitious composites, the estimated CO₂ emission provided by the cement industry equals to be 5–8% of its global emission [5]. Furthermore, extraction of virgin resources for the cement and aggregate production inevitably leads to their depletion, as a consequence of the robbery economy. Nevertheless, the significance of the construction sector is undeniable in terms of meeting social needs and increasing people's quality of life [3]. For this purpose, high-quality materials with desired properties for special applications are required. Simultaneously, based on the abovementioned issues, attention has been paid to reducing both production cost, and most notably, environmental impact of construction materials. To accomplish this objective, the construction sector is shifting away from raw materials and semi-finished products, such as natural aggregates and cement, in favor of more environmentally friendly, alternative materials, which are principally wastes or by-products derived from various industries [6]. According to the literature, the most commonly used waste materials are known as Supplementary Cementitious Materials (SCMs) [3]. Their ability to replace certain cement dosage in composite's binder blends is mainly associated with their pozzolanic activity, i.e., ability to react with Portlandite to form a secondary calcium silicate hydrate (CSH) phase, during the cement hydration process [7]. Some SCMs might be also used as fine aggregate replacement while coarser particle size diameters are more suitable in this case [8]. Most notably, such applicability of industrial wastes enables the production of more sustainable cementitious composites without deterioration of their mechanical properties. Additionally, taking into consideration the potential to solve waste management problems, it is found to be a prudent course of action, promoting a more sustainable, low-carbon, and circular economy. Therefore, research on the recycling of industrial wastes in mortars and concretes is of both scientific and industrial interest, thereby focusing researchers' attention all over the world. Nonetheless, despite the fact that a huge number of various SCMs were investigated, mainly fly ash, ground-granulated blast furnace slag, and silica fume, have already been consolidated in large-scale industrial applications [9]. Recently, various waste materials derived from the petrochemical industry, i.e., Oil Refinery Wastes (ORWs), attracted researchers' attention as promising materials capable of being reused as an alternative resource material in the construction industry. Considering that, this paper presents a literature review on the applicability of various ORWs in cementitious composites from the sustainable development point of view.

1.2. Types of Oil Refinery Wastes

Currently, life without petrochemical products, such as fuels, monomers, and organic chemicals, seems to be unimaginable, as they are commonly used for our daily ac-

tivities or are precious semi-finished products for other industries. Therefore, the significance of the oil refinery industry is unquestionable, and thus, the substantial development of this sector was observed recently. On the other hand, oil and natural gas refining processes and numerous related activities are closely associated with considerable amounts of oil refinery wastes generated in different forms. In general, those wastes might be divided into three main categories as presented in Figure 1.

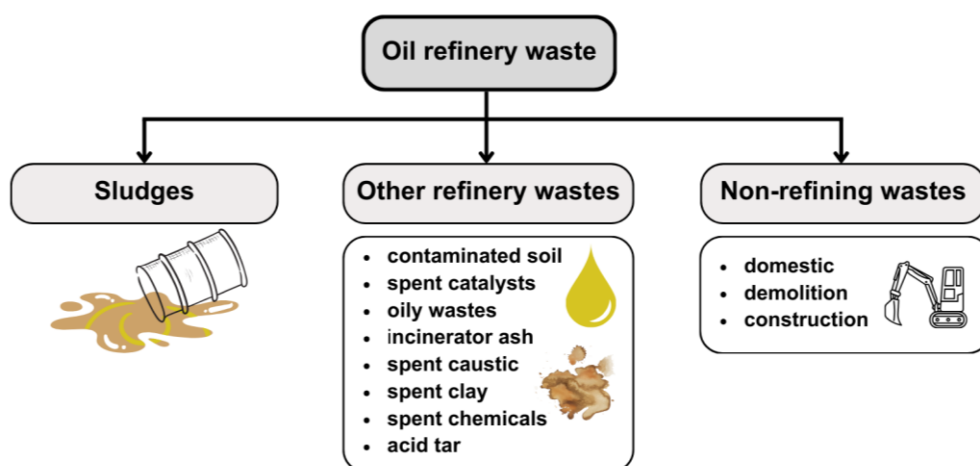


Figure 1. Types of oil refinery waste.

Nowadays, the general ORW recycling is unfortunately limited, as they contain various hydrocarbon compounds and heavy metals, adsorbed from crude oil resources during the refining processes. In this regard, the majority of solid ORWs, such as spent catalysts or waste process equipment, are disposed of in landfills. Meanwhile, liquid ORWs, i.e., various sludges, require complex methods of treatment, including thermal, mechanical, biological, and chemical techniques, which are generally costly [10]. Currently, new installations of hydrotreatment facilities, reforming, catalytic cracking, sulphur recovery, and various emission abatement techniques are launched to raise both the quality of products and overall refinery efficiency, whilst reducing gases emission. As a consequence, an upward trend was observed in the amount of waste catalysts produced [11]. Nonetheless, it should be mentioned that refinery catalysts and facilities are designed for specific conditions in the process to be used in [12]. What is more, different refineries process different types of crude oil resources. Consequently, ORWs generated all over the world vary in their chemical compositions, properties, structure, and contaminants. Considering this, an individual approach is required in terms of appropriate ORW management and potential recycling. Different types of oil refinery waste are presented in Figure 2.

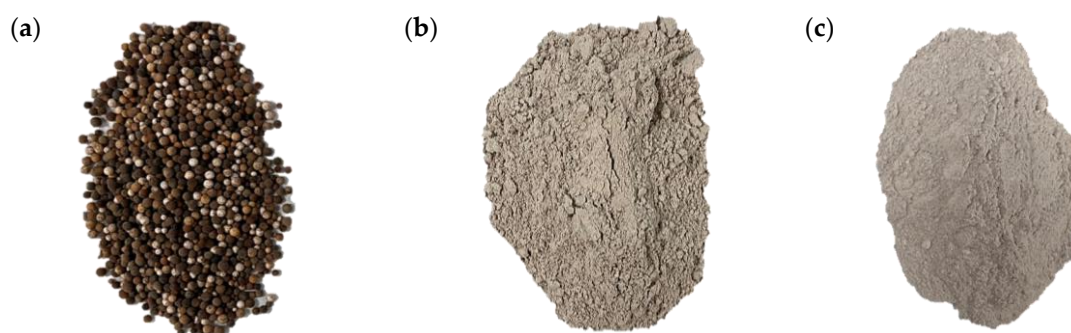


Figure 2. Oil refinery waste: (a) molecular sieves; (b) Claus and Hydrosulfreen; (c) ECat.

1.3. The Recycling of Oil Refinery Wastes in the Construction Sector

The issue of comprehensive reduction in the total environmental impact is of high priority for the petroleum industry. For this purpose, integrated development is required not only in terms of waste management issues. Unfortunately, as previously mentioned, the recycling of ORWs is significantly limited, and thus, instead of being reused, plenty of them require various utilization methods, such as landfilling. Apart from rising disposal costs and economic losses for a company, following procedures might cause environmental pollution and pose serious health risks [3]. It is therefore that undesired chemical contaminants, while released to soil and water, might poison natural flora and digestive systems of animals, thereby contributing to the general degradation. Furthermore, dusty wastes might be moved around by wind, and thus, the risk is spread on a larger scale. In terms of solving this problem, the recycling of oil refinery wastes in cementitious composites seems to be a reliable research direction. Overall, from the technical point of view, solid ORWs might be used as a cement or fine aggregate partial replacement. Meanwhile, those in liquid form might be used as a modifying admixture, plasticizing freshly mixed concrete [10]. Nonetheless, according to the literature, mainly spent catalysts withdrawn from the fluid catalytic cracking (FCC) unit were examined. The role of the FCC process is significant in every oil refinery, as it allows the production of both high-octane hydrocarbon components and low-carbon olefines, valuably used in blending high-quality commercial fuels and as a resource (monomer) for polymer material manufacturing, respectively. The cracking reaction requires a zeolite-based catalyst, which becomes deactivated over a period of time used in the process due to oil impurities adsorption and thus becomes the largest catalyst waste category in refineries [11,13]. It is vital that the incorporation of waste FCC catalyst as a partial replacement cement or sand enables the immobilization of heavy metals within the matrix of the hardened composite. That was confirmed by Su et al. [14], as the concentrations of heavy metals leached from waste FCC-substituted mortars were lower than in case of raw waste material. Additionally, organic compounds (coke deposits) might be efficiently eliminated from waste's structure through the appropriate chemical methods, e.g., oxidation, thereby improving their performance [13]. It should be pointed out that cementitious composites without their general quality deterioration were prepared with the incorporation of spent FCC catalyst derived from Lithuanian [8] and Portuguese refineries [9,15]. What is more, some of their properties have been improved, after a certain dosage of spent FCC catalyst was supplied. In general, this might be attributed to the outstanding pozzolanic activity of the catalyst, which is associated with its very high specific surface area, provided by high porous crystalline structure of zeolite, and most notably aluminosilicate chemical composition [9].

Nonetheless, many research gaps still deny it from the industrial implementation. What is more, plenty of other ORWs have been slightly investigated or have not yet been investigated, and thus, there is considerable room for exploration. Considerably, a comprehensive approach and extensive research are required to consolidate them as a sustainable resource material for the construction sector. This might be especially achievable in Poland, as there is the biggest oil refinery in Central and Eastern Europe. The amount of waste materials generated there in 2020 accounted for 291,600 tons, excluding municipal wastes [16]. Furthermore, apart from waste FCC catalyst, other ORWs are also accessible there. These include waste sulfur recovery catalysts, i.e., those derived from Claus and Hydrosulfreen processes, and waste molecular sieve residues. It should be also mentioned that Poland is one of the most important cement producers in Europe [17], which also highlights the possibilities for such investigations that are planned by the authors right there. Considering the above, the attention should be paid to systematizing the current state of knowledge concerning a comprehensive approach to the applicability of various ORWs in the construction industry. For this purpose, already investigated results must be

clarified and compared. In this regard, the scope of this paper includes a conducted literature review. As such, limitations and chances were highlighted, and some research gaps were determined. On the basis of the latter, some new research directions and trends were finally proposed. Focusing on them might be vital for the future tests, aimed at the industrial implementation of ORWs as green resource materials for the construction sector.

2. Review Methodology and Results

To provide the relevant literature data, the number of publications over the past 20 years was checked by implementing the ScienceDirect Elsevier database. Figure 3 presents the number of publications in the last 20 years that contain the word “concrete” and the phrase “oil refinery waste” in the article. Given the current number of publications in 2025, it can be assumed that it will exceed 500 publications by the end of the year.

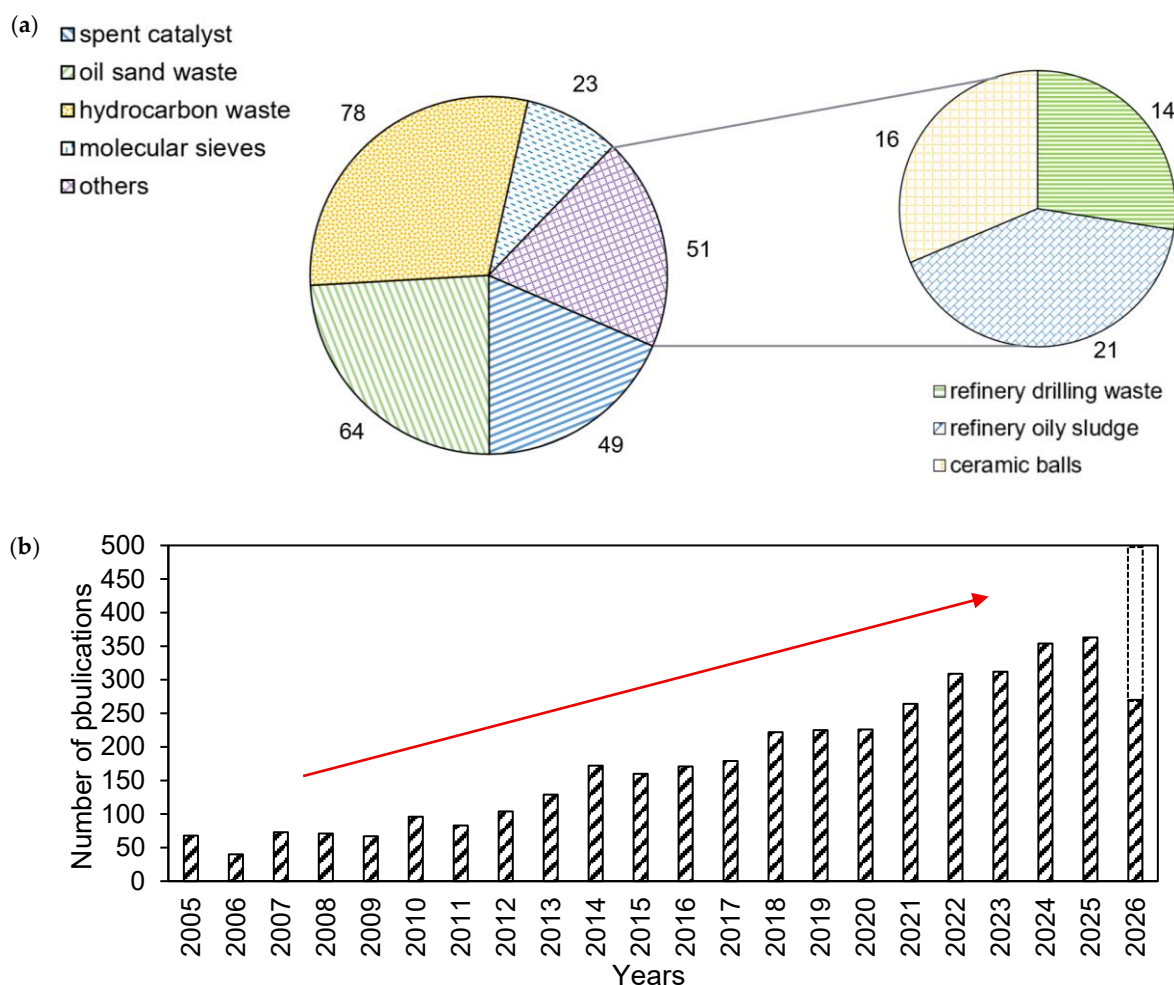


Figure 3. Research interest in the topic of refinery waste: (a) type of waste used; (b) the number of publications in the given years that contain the word “concrete” and the phrase “oil refinery waste” in the article (data on 24 June 2026).

The subject of ORWs in construction materials has been known for a long time, but the interest has seriously increased since around 2013, with particular growth in the last three years. Given the current number of publications in 2026, we can expect that by the end of the year, the total will exceed 500. As such, Figure 3 presents the number of publications devoted to the applicability of particular ORWs in cement materials. For this purpose, a formula was used that searches for the words “refinery waste” in the title, keywords, or abstract, and “oil refinery waste AND (concrete OR mortar)” in the article. The

phrase “oil refinery waste” searched in the article was replaced with several examples of popular ORWs. As such, the highest number of results was obtained for hydrocarbon waste, molecular sieves, and spent catalysts. The interest in refinery waste was also checked in Google Trends, as shown in Figure 4.

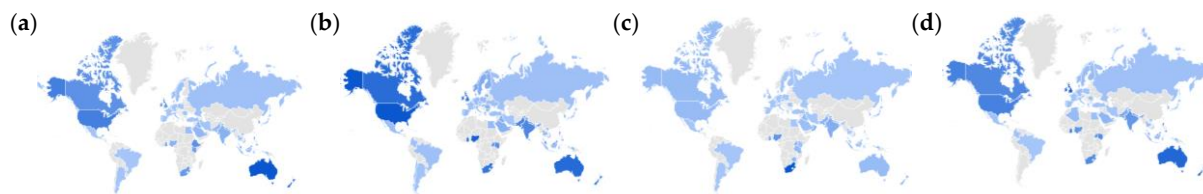


Figure 4. The interest in words: (a) concrete; (b) oil; (c) refinery; (d) waste (origin: Google Trends, 24 June 2026). (The color intensity corresponds to relative search interest, with darker blue denoting higher interest.)

The greatest interest in the searched phrase was noted in India and the United States. It is worth noting that both of these countries play a crucial role in the refining sector—the United States as the largest producer and India as one of the largest crude oil consumers [18]. Moreover, there is little interest in such research direction in Europe, proving that it is worth expanding the state of knowledge and conducting research activities on ORWs derived from this region.

3. State of the Art Knowledge

In the subsequent parts of the paper, the effects of incorporating ORWs in cement composites on their numerous performances in different states have been listed.

3.1. Effects of Using ORWs on the Fresh Properties of Concrete Mix

Table 1 summarizes the results of the state-of-the-art research on the effect of utilizing ORWs in cementitious composites on the properties of fresh concrete mix. It was noted that most studies focus on replacing cement with waste material. In most cases, replacing cement with catalyst causes a decrease in the workability of mixtures, which may be due to the shape of the catalyst particles. Adding a catalyst also results in a shorter binding time and less bleeding. In general, the use of catalysts shortens the setting time, which is useful for quick installation but troublesome in laying and transport. The assessment shows that the use of substitutes should be limited to 10–20% in order to maintain workability and controlled setting time. Liquid fractions can act as plasticizing modifiers, which opens up an interesting direction for research.

The use of ORWs in cement-based composites is also associated with certain limitations, resulting primarily from the variability in the properties of this waste material and its impact on the consistency of concrete mixtures. A reduction in workability may increase the need for chemical admixtures, which could negatively affect the economic and environmental benefits of using waste. Furthermore, changes in setting time can cause practical difficulties during mixing, transport, and placement of the mixture, especially in large-scale construction projects. The non-uniform properties of catalyst particles and other waste materials can also make it difficult to achieve consistent fresh concrete mix properties. Therefore, further research is necessary to optimize the proportion of ORW admixture and minimize its adverse effects on concrete properties.

Table 1. Effects of using ORWs on the fresh properties of concrete mix.

Type of Oil Refinery Waste	Application	Properties Tested	Results	Source
Oil-refinery spent catalyst	As an additive to the concrete mix, a substitute for fly ash	Density	When ECAT is added, the concrete mix's density is decreased.	[9]
Spent catalyst	Cement subtype in the amount of 10%, 20%, and 30% of cement in SCC mixtures	Flowability (slump flow diameters)	Larger slump flow diameters are obtained which means improved flowability.	[15]
		Viscosity (V _{tunnel} flow and t ₅₀₀ times)	Every mixture satisfies the research viscosity requirements outlined in European standard EN 206-9.	
		Passing ability (L-box ratios)	L-box standard requirements for SCC concretes with 30% FCC are not met.	
Spent catalyst	Substitute of fine aggregate with 5–15%	Workability	A decrease in workability and compaction is achieved.	[14]
Spent catalyst	Cement subtype in the amount of 20%	The setting time	Adding the catalyst reduces the setting time.	[19]
Ecat/Epcat	Replacement of cement with 5%, 10%, and 15%	Workability	More plasticizer has to be added to achieve the desired workability for greater substitution.	[20]
Spent catalyst (ECat and EP-Cat)	Cement subtype in the amount of 5%, 10%, and 15%	Flowability	A higher percentage of cement substitution results in a fall in the flowability.	[21]
		Bleeding	Bleeding decreases with a greater percentage of substitution. Bleeding in EPcat is less significant than in Ecat.	
		The setting time	As the degree of substitution increases, the setting time decreases.	
Spent equilibrium catalyst	Cement substitute in the amount of 15% in UHPFRC	Workability	The addition of the catalyst reduces workability by 24%	[22]
Fluid catalytic cracking catalyst residue	Cement subtype in the amount of 6%, 10%, 15%, and 20%	Autogenous shrinkage	The shrinkage is similar.	[23]
		Flowability	The inclusion of ECat results in a less flowable mix.	
		The setting time	Both of them are found to be shorter, as SO ₃ content decreases with increasing FC3R incorporation levels.	
Waste fluid catalytic cracking catalyst	Cement subtype in the amount of 10%, 20%, and 25% in SCC mixtures	Flowability (slump flow diameters)	The addition of 10% FCC results in larger slump-flow diameters, whereas the addition of 20% and 25% results in smaller diameters.	[24]
		Viscosity (V _{tunnel} flow and t ₅₀₀ times)	All mixtures satisfy the requirements set out in European standard EN 206-9 in a research viscosity—VS2 and VF1.	
		Passing ability (L-box ratio and J-ring)	All FCC mixtures receive the same grade as the reference mixture.	
Fluid catalytic cracking catalyst residue	Cement subtype in the amount of 15% and 30%	Viscosity (V _{tunnel} flow and t ₅₀₀ times)	All mixtures satisfy the requirements set out in European standard EN 206-9 in a research viscosity—VS2 and VF1.	[25]

Fluid catalytic cracking catalyst	Replacement of 15% by weight of cement	Passing ability (L-box ratio and J-ring)	All FCC mixtures receive the same grade as the reference mixture.	[26]
Spent fluid cracking catalyst	Cement subtype in the amount of 3%, 6%, and 12%.	Workability	The catalyst's addition decreases the workability.	[27]
Spent fluid catalytic cracking catalyst	Replacement of cement with 10% in combination with 20% FA	Flowability (flow table test)	In most cases, the flow diameter is greater for that of FCC-added blends.	[28]
Organic fraction of oil waste	As a modifying admixture	Workability	Freshly mixed concrete becomes plasticized when OFOW is added.	[10]
Treated oil sand waste	Replacement of fine aggregate with 10%, 20%, 30%, and 40%	Workability	Concrete workability is significantly affected by reducing slump and requiring increased super-plasticizer dosage.	[29]
Contaminated sand	Sand contaminated with oil up to 20%	Density	Density decreases as oil content increases.	[30]
Used engine oil	As chemical admixtures	Workability	Workability improves at low dosages (up to 1% for high-strength concrete and up to 6% for normal-strength concrete) by acting as a water-reducing agent through its sulfonate groups.	[31]

3.2. Effects of Using Oil Refinery Wastes on the Physical and Mechanical Properties of Concrete

Table 2 summarizes the results of the state-of-the-art research of the effect of utilizing ORWs in cementitious composites on the various properties of hardened concrete.

Table 2. Effects of using ORWs on physical and mechanical properties of hardened concrete.

Type of Oil Refinery Waste	Application	Properties Tested	Results	Source
The organic fraction of oil waste	Hydrophobic plasticizer for building of materials up to 3% weight of cement	Compressive strength	The addition of waste improves the compressive strength.	[32]
		Flexural strength	The addition of waste improves the compressive strength.	
		Porosity	The porosity has decreased.	
Oil-refinery spent catalyst	As an additive to concrete mix ranging from 16,7 and 33%, a substitute for FA	Compressive strength	A mixture with 33% ECat shows a lower strength as all samples with FA.	[9]
		Dynamic modulus of elastic	Concretes with the addition of ECat show lower values of the dynamic modulus of elasticity than mixes with FA.	
		Water absorption	The ECat in concrete increases water permeability.	
Waste oil-cracking catalyst	Replacing cement with 5%, 10%, and 15% of the wFCC catalyst	Chloride migration	The ECat in concrete does not increase the risk of corrosion of the reinforcement under external chloride attack.	[33]
		Water absorption	All mortars that contain the catalyst exhibit reduced water absorption.	
		Chloride migration	The resistance to chloride penetration is increased by using a waste catalyst.	

		Carbonation	The use of a waste catalyst makes it more susceptible to carbonation.
Spent catalyst	Replacing cement with 10%, 20%, and 30% in SCC	Compressive strength	The use of 10% and 20% spent catalyst delays endurance development in the first 28 days. After this time, the concrete in the addition of 30% achieves a similar strength. [15]
Spent catalyst	Replacing cement with 10% and 35%	Compressive strength	An FCC content of 10% shows a higher compressive strength than the reference sample and the sample with 35% FCC. [34]
Spent catalyst	Replacing cement with 15%	Flexural strength	After 3, 7, 14, and 28 days, results were comparable to the reference sample.
		Compressive strength	Up to 3 days with the catalyst, it is lower; after 7 days, it starts to be slightly higher. The highest value is noticed after 28 days. [35]
Spent catalyst	Replacing cement with 10% and 15%; replacing sand with 10%.	Compressive strength	Samples with FCC obtain a higher value of compressive strength than those without FCC. [36]
Spent catalyst	Replacement of cement with 5%, 10%, and 15%	Compressive strength	For all w/c ratios, mortar with 5% substitution shows higher strength.
		Water absorption of mortars	Mortars with Ecat and EPcat have comparable or higher water absorption. This value increases with the increasing substitution level and is higher in case of Ecat incorporation. [21]
Spent catalyst	Replacement of sand in ultra-high-performance concrete.	Compressive strength	The compressive strength is within similar limits. [12]
		Resistivity	A decrease in resistivity is noted with an increase in the replacement ratio of the sand.
Spent catalyst	Replacement of 25% by cement	Compressive strength	A catalyst is added, and the compressive strength is increased at 7 and 28 days. [37]
		Flexural strength	The bending strengths are found to be similar.
Spent catalyst Ecat/EPcat	Replacement of cement with 5%, 10%, and 15%	Compressive strength	Strength rises with hardening time and surpasses that of additive-free samples. [20]
Spent catalyst	As fine aggregate replacement in 5%, 10%, and 15%	Compressive strength	The addition (5% and 10%) Ecat increases the strength (w/c = 0.55). The addition of 15% causes a significant reduction, irrespective of the investigated conditions. [14]
		Water absorption	Increased absorption of water has been observed.
Spent equilibrium catalyst	Cement substitute in the amount of 15% in UHPFRC	Compressive strength	The addition of catalyst causes a slight decrease in compressive strength. [22]
		Elastic modulus	The elastic modulus after 28 days is increased by up to 3% compared to that of the control sample.
Spent catalyst from two different sources	As cement replacement in 2%, 4%, 6%, 8%, and 10%	Mechanical properties	The application of both cement substitutes results in a weakening of the long-term mechanical properties of composites. [38]
	As sand replacement in 5%, 10%, 15%, 20%, and 25%	Compressive strength	Replacing fine sand in 5% and 10% gives higher strength after 7 and 28 days. At higher substitution levels, the increase is no longer observed.
Purified and unpurified catalyst	Replacement of 10%, 20%, and 30% by weight of cement	Compressive strength	Samples with pFCC show better strength values. The use of 10% and 20% of waste catalyst leads to the enhancement in CS for FCC and pFCC. [13]

Catalytic cracking catalyst residue	Replacement of cement with 6%, 10%, 15%, and 20%	Flexural strength	Early flexural strength decreases with increasing substitution levels. After 7 days, it is of a similar value.	[23]
		Compressive strength	Early compressive strength decreases with increasing FCC, but after 7 days, the strength increases with the increasing amount of the catalyst.	
Fluid catalytic cracking catalyst residue	Replacing cement with 10% and 20%	Compressive strength	After 7 days, mixtures containing up to 20% wFCC show an increase in strength. The inclusion of 25% of the catalyst in FCC causes a delay in the strength in the first 28 days, but after this period, their strength is also slightly higher than that of the reference.	[24]
Fluid catalytic cracking catalyst residue	Replacement of cement with 15% and 30%	Flexural strength	The flexural strength of the samples is similar to or greater than that of the control sample, except for the unmachined mineral admixture.	[25]
	Replacement of cement with 5–30%	Compressive strength	The maximum compressive strength is obtained for the replacement of 15% and 20% of cement.	
	Replacing sand	Compressive strength	A continuous increase in strength is observed with the increasing degree of substitution.	
Catalytic cracking	As a cement (15%) or sand (10%) replacement in cement mortars	Strength value in mortar samples cured in temp. of 5 and 20 °C	All mortars reveal strength gain, in comparison to the reference, for all curing temperatures, as confirmed by pozzolanic activity of FCC. The use of FCC in cold weather mixing is recommended especially as a sand substitute.	[39]
	Replacing sand	Compressive strength	The compressive strength is similar and higher than that of the control sample.	
Cracking catalyst	Replacement of 15% by weight of cement	Compressive strength	The compressive strength is higher.	[26]
Spent fluid cracking catalyst	Replacement of 3%, 6%, and 12% by cement	Compressive strength in salt and tap water	Replacement has a positive effect on the strength when curing in salt water. An increase in the level of SFCC replacement leads to a slight, constant decrease in the strength of samples cured in tap water.	[27]
		Permeability	There is a steady increase in air permeability with an increase in exchange.	
		Carbonation	As the amount of cement replaced by SFCC increases, the depth of carbonation increases.	
		Chloride migration	The resistance to chloride penetration increases as more SFCC is substituted for cement.	
Spent fluid catalytic cracking catalyst	Replacement of cement with 10% in combination with 20% FA	Compressive strength	Strength increases with the addition of FCC after 7, 28, and 90 days.	[28]
		Flexural strength	Flexural strength ratings are generally comparable to and marginally below the standard values.	
Spent fluid-catalyzed catalytic cracking catalysts	Replacement of cement in high-density cement-based materials (HDCM)	Compressive strength	After 28 days, the strength of HDCM containing 80 kg/m ³ increases by 6.6%. HDCM containing 150 kg/m ³ also shows good mechanical properties.	[40]

Contaminated sand	Used sand contaminated with oil up to 20%	Porosity	The porosity increases with the amount of substitution, but HDCM containing ORWs still has good durability and a compact microstructure.	[30]
		Compressive strength	Strength increased at 1% oil contamination. Concrete containing fine sand from 2% to 6% contamination shows lower strength. Increasing the oil content from 10% to 20% results in a significantly lower strength.	
		Tensile strength	Strength increases at 1% oil contamination. At oil contamination levels higher than 1%, the tensile strength decreases.	
Contaminated sand	Used sand contaminated with oil up to 25%	Compressive strength	The reduction in strength of concrete is a function of the concentration of oil in the sand. The higher the concentration, the greater the reduction in strength.	[41]
Contaminated sand	Sand contaminated with crude oil products up to 1.5%	Compressive strength	Sand contaminated with kerosene and diesel fuel can adversely affect the strength of concrete.	[42]
Treated oil sand waste	Replacement of fine aggregate with 10%, 20%, 30% and 40%	Compressive strength	Compressive strength is progressively reduced with increasing replacement rates.	[29]
Used engine oil	As chemical admixtures	Compressive strength	An optimal dosage of 2% UEO increases strength by more than 3%, whereas dosages exceeding 5% result in a decrease in strength.	[31]
		Microstructure	SEM observations revealed that concrete with 2% UEO exhibits a denser microstructure with fewer micropores and cracks compared to the control, a result of the filling effect of well-dispersed particles.	

Although some cases reported a decrease in compressive strength, the analysis of all the work indicates that replacing cement with up to 20% spent catalyst causes a slight increase in compressive strength or does not change it. The noted differences may be due to different sources of the catalyst and its properties. It is noteworthy that the catalyst in purified form shows better mechanical properties than the unpurified catalyst. It is worthwhile to deepen research in this direction and confirm these conclusions with more results. In addition to compressive strength, bending strength and chloride penetration were also studied. The results obtained do not make it possible to unequivocally state the effect of the catalyst on these properties. Compressive and flexural strengths of concretes containing oil-contaminated sand decrease because of the formation of inferior bonds.

However, the use of spent catalysts as a cement substitute also has certain limitations. Variations in the composition of the catalyst, resulting from its origin and the processing method used, make it difficult to predict the long-term properties of concrete mixtures and limit the ability to establish universal cement replacement ratios. Another disadvantage is the potential presence of impurities and residues in untreated catalysts, which can negatively affect hydration processes and the durability of cementitious composites. Additional processing increases the complexity and costs of its use. Furthermore, most studies focus primarily on short-term mechanical properties, while the impact of spent catalysts on long-term durability, environmental stability, and resistance to aggressive agents still requires further analysis.

To present a clear outlook on the impact of the addition of spent FCC catalyst, primarily investigated ORWs were evaluated based on the most essential mechanical param-

eter of cementitious materials, i.e., compressive strength (CS). Figure 5 was prepared based on results obtained from 8 independent research works. As such, the changes in CS values in relation to the reference ones are shown in percentages for three cement replacement levels, i.e., 10%, 15%, and 20% by mass.

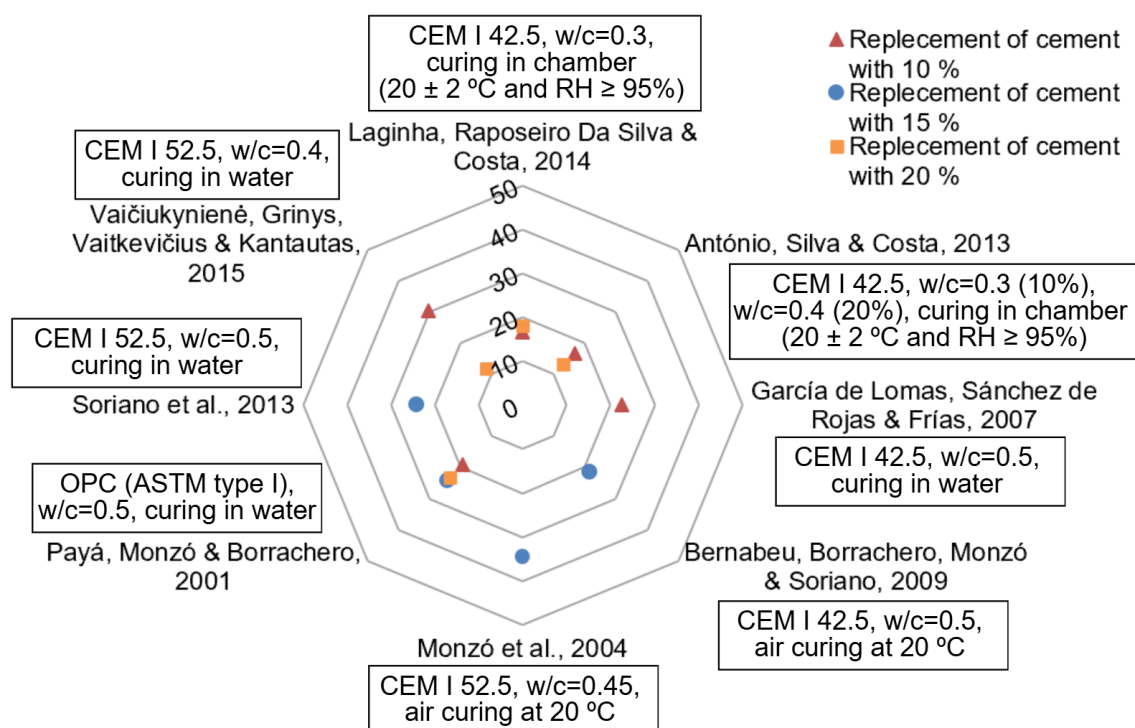


Figure 5. The effect of replacing cement with spent FCC catalyst on compressive strength after 28 days of curing [13],[15],[23],[24],[34],[35],[36],[39].

As it is presented in Figure 5, a few papers reported that the replacement of up to 15% of cement with spent FCC catalyst led to the increase in CS of hardened composites by up to 45%. Figure 6 illustrates the percentages of research work emphasizing on several ORW types in which their addition to cementitious composites revealed positive or negative impact on the basic performances, i.e., consistency and compressive strength. The lack of a sufficient number of studies in case of adsorbents, such as ceramic balls derived from molecular sieves and oil sludges, presents the research gaps in this area.

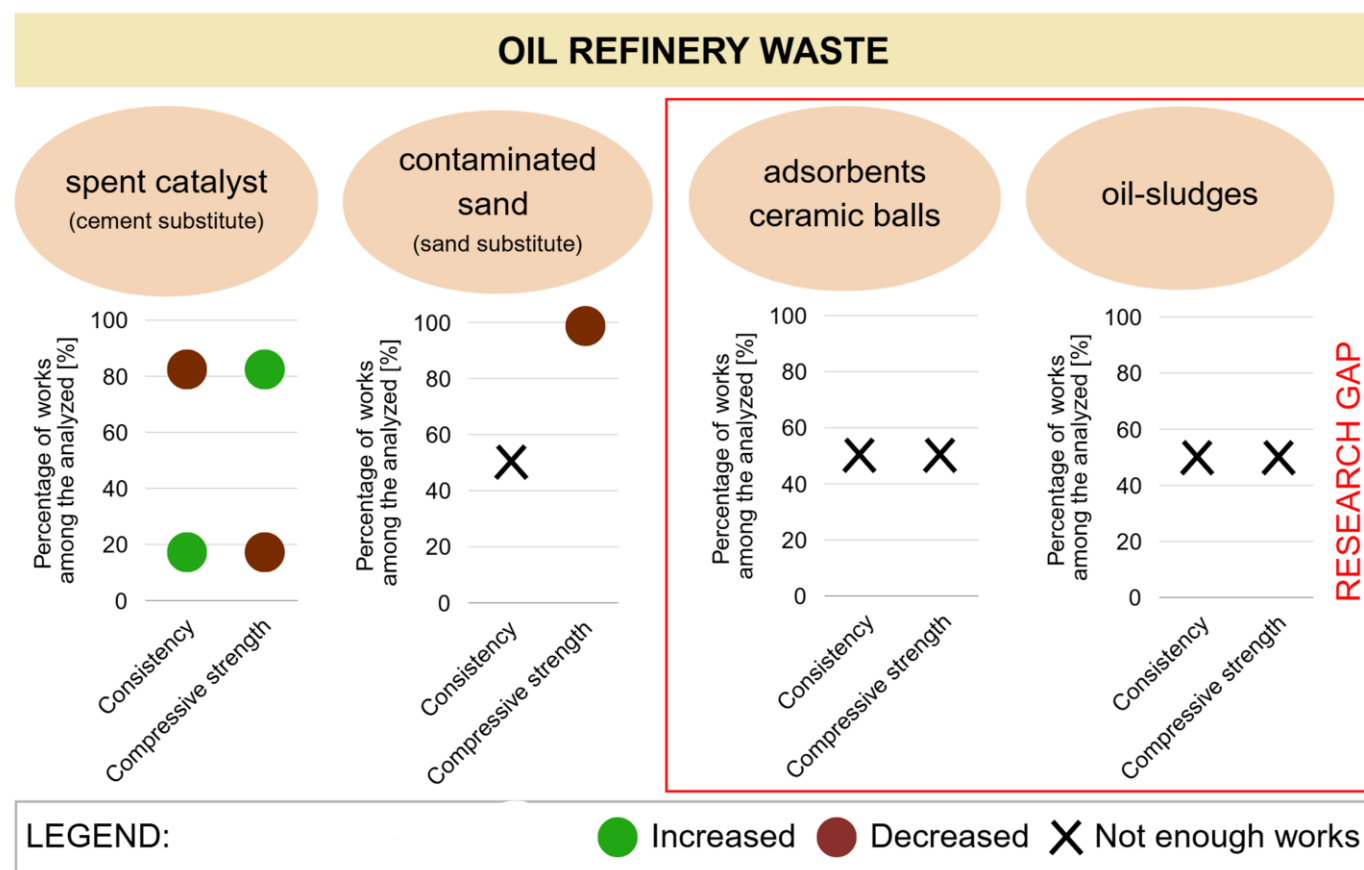


Figure 6. The percentages of work carried out on several ORWs, showing positive or negative impact of the performances of cementitious composites.

3.3. Chemical Methods of Investigation of ORWs and Cementitious Composites

Table 3 lists the broadly understood chemical analysis and valorization methods of ORW materials aimed for increasing their reactivity in cement systems, as well as their impact on various properties in case of both ORWs and ORW-blended cementitious composites.

Table 3. Effects of using ORWs in pure and valorised forms on properties of concrete together with physicochemical properties of ORW materials.

Type of ORW	Application	Properties or Parameters Tested	Achievements and Results	Source
Spent fluid catalytic cracking catalyst (FC3R)	As a ground material incorporated in Portland cement pastes	Mean particle size diameter as a function of grinding time	After 20 min of grinding, it is reduced to around 20 µm. Grinding FC3R is conducted to increase its reactivity.	[7]
		The concentration of hydration products in cement paste	CSH/CASH phases increase, whilst Ca(OH) ₂ diminishes, as the FC3R content increases, based on TGA measurement.	
		Fixed Ca(OH) ₂ percentage	Fixed lime increases as the cement replacement level rises, with 15–20% found to be optimum.	
Spent equilibrium catalyst (Ecat) and electrostatic	As a cement substitute in the range of 6%,	Chemical composition and element analysis	Both catalysts exhibit similar chemical composition (mostly made up of SiO ₂ and Al ₂ O ₃); however, EPcat contains more heavy metals than Ecat.	[21]

precipitator catalyst (EPcat)	10%, 15%, and 20%	Mean particle size diameter and specific surface area	The average particle size diameter of Ecat is about 10 times larger than that of EPcat while consequently its specific surface is about three times that of EPcat.
		pH value	EPcat is more acidic than Ecat, as it contains more sulfur.
		Crystal structure of catalysts and substituted mortars	Both catalysts have similar crystal structure, close to that of Faujasite zeolite. Crystal composition of every hardened mortar is also similar.
		Toxicity analysis of catalyst and hardened mortars	TCLP analysis confirmed that the amount of heavy metals leached from both Ecat and EPcat is low and meets the regulatory standards in Taiwan.
		Water absorptivity of catalysts	EPcat has higher water absorptivity than Ecat.
		Hydration heat	The hydration heat of mortars incorporating 10% and 15% of catalysts is close to the unsubstituted one, as these waste catalysts are exothermic.
Spent fluid catalytic cracking catalyst (FC3R)	As a cement substitute of 6%, 10%, 15%, and 20%; as a partial sand replacement (0–30%) in ultra-high-performance concrete	Chemical characteristics of blended cements	Blended cements reveal similar LOI value and chloride content, in comparison to the plain one. SO ₃ content decreases with the increase in cement replacement level, in contrast to increasing IR value. [23]
		Pozzolanicity of blended cements	Ca ²⁺ and OH ⁻ ions content in the solution decreases with the increase in FC3R content in the cement (Fratini method). Vital pozzolanicity is noticed when FC3R content is 15% and higher.
Spent equilibrium catalyst (ECat)	As a sand replacement (0–30%) in ultra-high-performance concrete	Specific surface and water absorption of ECat	High specific surface of ECat (157,070 m ² /kg) provides its significant water absorption, i.e., 30% by mass after 24 h, according to EN 1097-6.
	As a cement replacement (15%) in cement pastes	Direct pozzolanic activity	According to the Modified Chapelle test method, 1540 mg of Ca(OH) ₂ is consumed by 1 g [12]
		Chemical composition and density of ECat	ECat mainly consists of Al ₂ O ₃ and SiO ₂ , which accounts for 54.45% and 40.30% by mass, respectively, while its density equals to by 2660 kg/m ³ .
Spent fluid catalytic cracking catalyst (FCC)	As a cement replacement in the range of 15% in cement pastes	Mean particle size distribution of FCC	In order to increase reactivity, FCC was ground for 20 min to achieve a mean particle size of 19.73 µm (laser granulometry).
	As a 30% cement substitute in cement mortars	Chemical composition, LOI, and IR values of FCC	FCC catalyst mainly consists of Al ₂ O ₃ (49.25%) and SiO ₂ (47.76%) determined by the XRF method. LOI and IR were found to be 0.51 and 0.00, respectively. [39]
		Fixed lime percentages in cement paste cured in temperatures of 5, 10, 15 and 20 °C	All pastes content revealed positive fixed lime percentages for all curing times and all curing temperatures, so that the pozzolanic reaction occurs at low temp.
Spent fluid catalytic cracking catalyst (FC3R)	As a 30% cement substitute	Chemical composition of FC3R	FC3R mostly consists of SiO ₂ (48.2%) and Al ₂ O ₃ (46.0%) [25]

ing catalyst (FC3R)	in cement mortars	Specific gravity (density) and bulk density of FC3R	Specific gravity of FC3R is found to be 2.45, while its bulk density accounts for only 0.863. This reveals the high porosity of particles.
	As a cement substitute (30%)		SEM analysis indicated the very porous appearance of FC3R particles. Their specific surface area equals to be extremely high (about 83,000 m ² /kg).
	in cement mortars and pastes (15%)	Structure of FC3R and its specific surface area	As FC3R is an aluminosilicate material with an extremely high specific surface, the demand for water might be higher. Considering, a plasticizing admixture is recommended.
		Water requirement to produce cement mixtures with FC3R	No flow decrease was observed, indicated that the effect of grinding FC3R (increasing fineness) on workability might be considered as negligible.
Waste fluid catalytic cracking catalyst (FCC)		FC3R grinding in relation to workability of freshly mix mortars	Grinding time (until 20 min) increases CS value of mortars with FC3R incorporation.
		FC3R grinding in relation to CS of hardened mortars	
	As a cement substitute (30%) in cement mortars and pastes (15%)	The impact of grinding time on the AI value of mortars containing FCC catalyst	At the 28th curing day, AI increased with longer grinding time, as it enhanced the reactivity of the FCC catalyst.
	As a cement (3%, 6%, and 12%) substitute in mortars	Secondary hydration products quantification	Secondary hydration products (CSH, CSAH, and CAH) were identified in hardened FCC- cement pastes by the TGA method. Simultaneously, Ca(OH) ₂ content was found to decrease. Both might be attributed to the pozzolanic reaction occurrence. [19]
Spent fluid cracking catalyst (FCC)	As a cement (3%, 6%, and 12%) substitute in mortars	Chemical composition of oxides of FCC	The FCC catalyst comprises mainly SiO ₂ and Al ₂ O ₃ and residual amounts of other species.
	As a cement replacement (10–30%) in self-compacting concretes with limestone powder	Specific surface area and specific gravity of the FCC catalyst	Its specific surface area was found to be 118 m ² /g, investigated using the BET method, while its specific gravity accounts for 2.17 g/cm ³ . Direct pozzolanicity was confirmed using electrical conductivity variation. The conductivity decrease was found to be 2.21 mS/cm after 2 min (more than 1.20 mS/cm), which is attributed to the decrease in Ca(OH) ₂ caused by the presence of FCC (pozzolanic reaction occurred). [27]
		Pozzolanic activity of the FCC catalyst	XRF analysis revealed that FCC mainly consists of Al ₂ O ₃ and SiO ₂ (52.81% and 39.59%, respectively), while the LOI was found to be 1.48% by mass. Its specific surface area, determined by nitrogen adsorption–desorption isotherm, equals to be 150 m ² /g. Specific density: 2.71 g/cm ³ and mean particle size: 86.05 µm. [15]
	As a partial cement replacement (0, 10%, 20%, and 25%) in self-compacting concretes	Chemical composition, LOI, specific surface area, specific density, and mean particle size of waste FCC catalyst	XRF analysis revealed that FCC mainly consists of Al ₂ O ₃ and SiO ₂ (52.81% and 39.59%, respectively), while the LOI was found to be 1.49% by mass. Its SSA, determined by nitrogen adsorption–desorption isotherm, equals to be [24]
Spent fluid cracking catalyst (FCC),	As a partial sand substitute (5%, 10%, and 15%) in cement mortars	Chemical composition, LOI, specific surface area, and specific density of waste FCC catalyst	

Spent equilibrium catalyst (ECat)	As a partial sand substitute (5%, 10%, and 15%) in cement mortars As a partial substitute of cement (0, 10%, 20%, and 30%) in cement pastes	Chemical composition, LOI, and mean particle size diameter of ECat	150,000 m ² /kg, and its specific density is 2.71 g/cm ³ . ECat mainly consists of SiO ₂ (51.69%) and Al ₂ O ₃ (41.12%), while the LOI was found to be 3.31%. The mean particle size diameter was measured as 68.5 µm.
		Bulk density and specific gravity	The bulk density of ECat is 0.88 g/cm ³ , while its specific gravity accounts for 2.48 g/cm ³ .
		Specific surface area and pore volume	ECat reveals a very high specific surface area, i.e., 249 m ² /g, and its pore volume is 0.265 cm ³ /g.
		Water absorption capacity of ECat	The absorption capacity of ECat (from the oven dry to the SSD condition) is 31%.
		Toxicity analysis of the catalyst	ECat meets the regulatory standards in Taiwan regarding the concentration of heavy metals leached and, thus, might be classified as non-hazardous.
		Toxicity analysis of hardened mortars containing ECat	The concentration of heavy metals leached from cement mortars containing ECat is lower than ECat.
Waste FCC catalyst (FCC) and purified waste catalyst (pFCC)	As a partial substitute of cement (0, 10%, 20%, and 30%) in cement pastes	Particle size distribution (PSD) and specific surface area of FCC and pFCC	Even though the PSD is identical in case of FCC and pFCC, the specific surface area of pFCC is higher than that of FCC (0.1525 m ² /cm ³ and 0.1403 m ² /cm ³ , respectively).
		Thermal analysis of FCC and pFCC (DTA)	The exothermal effect at about 604 °C was observed only for FCC sample. This might be attributed to elimination of oil pollutants from pFCC through H ₂ O ₂ treatment.
		Thermal analysis of hardened cement pastes sample containing 10% of FCC and pFCC	The amounts of Ca(OH) ₂ in hardened pastes are lower when FCC and pFCC are incorporated. This is due to the lower cement content and pozzolanic reaction which occurs in the system.
		The impact of purification process on the compressive strength of pastes	Samples exhibit higher CS values. At every substitution level, pFCC samples revealed strength enhancement compared with FCC. It indicates the profitability of purification process.

The role of materials science and chemistry is vital considering the recycling feasibility of various waste materials, such as ORWs, since their composition, contaminants, processing, properties, and microstructure are highly variable [10], and thus, such materials might provide different impacts on final cement products.

It should be stated that spent FCC catalysts are always mainly composed of Al₂O₃ and SiO₂ in different proportions with slight addition of Fe₂O₃. This finding reveals their pozzolanic activity in the cement system, even though that the proportions between those two oxides (alumina and silica) vary between 97/3 in the case of the alumina catalyst and 44/56 in the case of the silica catalyst. Hence, it is obvious that understanding the complete physical and chemical properties of ORWs, carried out by means of chemical methods, gives grounds to predict their impact on the final cement product [10].

It should be stated that spent FCC catalysts are mainly composed of Al₂O₃ and SiO₂ in the more or less equal mass ratio with slight addition of Fe₂O₃ [39]. In contrast, the proportion between alumina and silica oxides varies between 97/3 and 44/56 in the case of alumina catalyst. Hence, it is obvious that understanding the complete physical and chemical properties of ORWs, carried out by means of chemical methods, gives grounds

to predict their impact on the final cement product [10]. In general, the higher the Al_2O_3 and SiO_2 content in ORWs, the better the pozzolanic properties they exhibit [12,27,39], also probably due to the fact that the increasing content of those oxides means a lower LOI value. Nonetheless, the correlation of the chemical composition of ORWs with the impact on concrete is challenging due to the variabilities in concrete composition, substitution levels of cement, applied admixtures, and concrete components. However, it is noteworthy that pozzolanicity is affected not only by the chemical composition but also by the mineralogical form of silica and alumina oxides (a high amorphous content is highly preferred) and the specific surface area, an increase in which leads to superior pozzolanic activity but also enhances the water demand of ORWs (due to a higher surface area available both for chemical reaction and absorption of water). The knowledge on chemistry of ORWs might allow us to tailor and develop them for various applications from a technical, economic, and also environmental point of view. What is more, as it has been presented in Table 3, certain chemical methods, such as the purification of ORWs, enable the efficient elimination of undesired organic contaminants, which are the main factors retarding the cement hydration process [23]. As such, the pozzolanic activity and general performance of ORWs might be improved, resulting in higher quality of cementitious composites prepared from them. Therefore, the chemical purification of ORWs might be found as an interesting research direction for the future. Additionally, the efficiency of heavy metal binding within the matrix of the composite might be evaluated using toxicity tests, such as TCLP, carried out on both ORWs and ORW-included composites ([21]; [14]. Overall, the obtained results in Table 3 give highly valuable information regarding environmental and health risk assessment of such applicability of petroleum wastes, which might be crucial in terms of their implementation feasibility.

4. Research Gaps

Table 4 presents the number of studies in which the given properties of spent catalysts and cement composites were tested. The focus was put on this material as it appeared most frequently in the analyzed articles. For this purpose, a formula was used that searches the words “spent catalyst” in the title, keywords, or abstract and “cement/fine aggregate AND properties tested” in the article.

Table 4. The number of publications with tested properties (data on 8 December 2025).

Physical, Rheological, and Mechanical Properties of Cementitious Composites			Physicochemical Properties of ORWs and Cementitious Composites	
Properties Tested	The Number of Publications		Properties Tested	The Number of Publications
	Cement Substitution	Fine Aggregate Substitution		
Consistence	169	116	Chemical composition	114
Flowability	174	157	Mean particle size diameter	86
Viscosity	45	44	Bulk density	108
Passing ability	16	15	Specific gravity	42
Bleeding	7	3	Pozzolanic activity	51
The setting time	61	34	Specific surface area	231
Autogenous shrinkage	10	7	Water absorptivity	158
Volume change	182	147	LOI value	38
Workability	30	19	Chemical characteristics of loss on ignition	37
Compressive strength	89	52	Chemical characteristics of insoluble residue	48

Flexural strength	24	10	Chemical characteristics of sulfur trioxide content	7
Tensile strength	21	19	Chemical characteristics of chloride content	78
Porosity	105	95	Secondary hydration products quantification	13
Water absorption	115	95	Calcium hydroxide quantification	20
Dynamic modulus of elastic	2	2	Thermal analysis	256
Carbonation	26	16	pH value of the fresh mix	56
Chloride migration	17	10	Toxicity test of ORWs	0
Resistivity	32	33	Toxicity test of hardened composite	8
Permeability	28	17	Microstructure of hardened composite	16
Water absorption	115	95	Pore volume of ORWs	0
Hardness	17	13	Purification of ORWs	0
Abrasion	18	14		

Accordingly, the focus of analyzed articles was mainly placed on consistency, flowability, viscosity, and the setting time in the testing of the fresh mixes. On the other hand, from the properties of hardened concrete, the most frequently evaluated were compressive and flexural strength. In addition to tests carried out on concrete, there are also studies in the literature aimed at evaluating the suitability of the catalyst to be used as a substitute kaolin in ceramic materials, e.g., in tiles or frits [43].

Although the interest in utilizing ORWs in the construction sector is growing, they have not yet been thoroughly researched. The work focused mainly on the study of consistency, flowability, volume change, and compressive strength. The influence on dynamic modulus of elastic, autogenic shrinkage, hardness, and tensile strength was studied the least frequently. In addition, substitution of cement was studied much more frequently than in the case of aggregate, which leaves a lot of room for future research. Available studies on durability are limited, particularly with regard to resistance to sulfates, freeze-thaw cycles, and abrasion. These issues remain poorly understood and represent a significant research gap. Further research on the long-term durability of these materials is necessary.

Moreover, according to the literature, ORWs were mostly investigated in the original form, i.e., straight from the process or only after grinding, less often after various chemical activation and purification operations, mentioning that usually few analytical methods were used to evaluate their efficiency. Hence, in this case, the complete waste properties before and after the purification processes were not compared with each other and with the impact on concrete, with special emphasis on its toxicity. Such research gaps are worth filling as the purification of ORWs might increase their value as a resource for cement production (the elimination of organic deposits might reduce the loss on ignition value of ORWs and hence increase the silica and alumina content per gram of ORWs). Despite this, the purification might allow for reducing the risk associated with the toxicity of cement composites to a minimum. However, this direction was not investigated in the literature. The general ideas for the purification of several types of ORWs, presenting the perspective on future research, are shown in Figure 7.

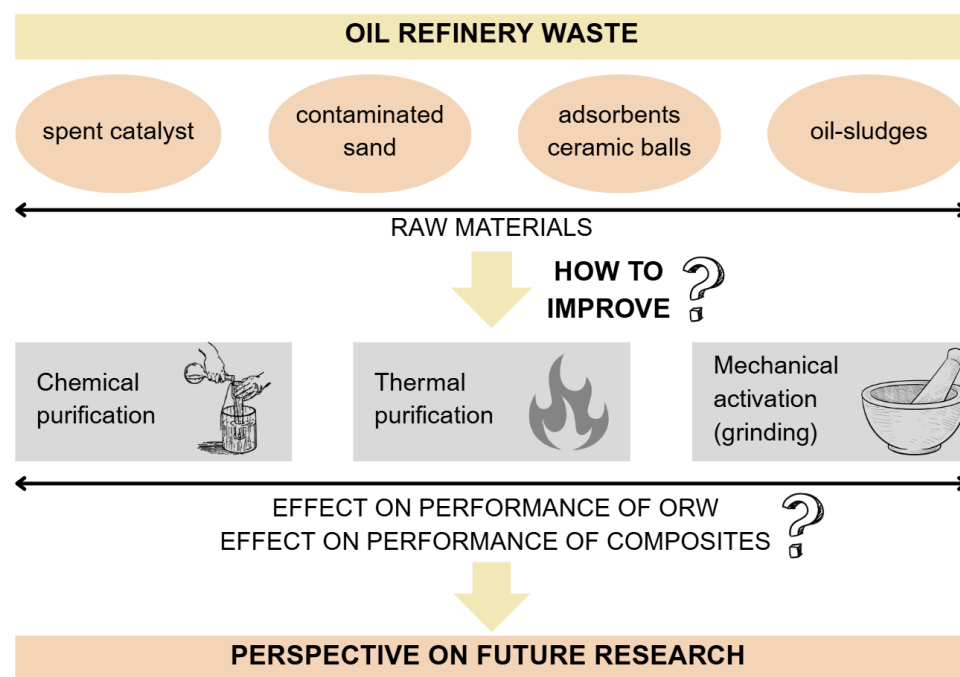


Figure 7. General ideas for the purification of ORWs presenting the perspective on future research.

Accordingly, numerous research gaps are provided in this area, and thus, there is still huge room for exploration in the future. The most essential research gaps are outlined in Figure 8.

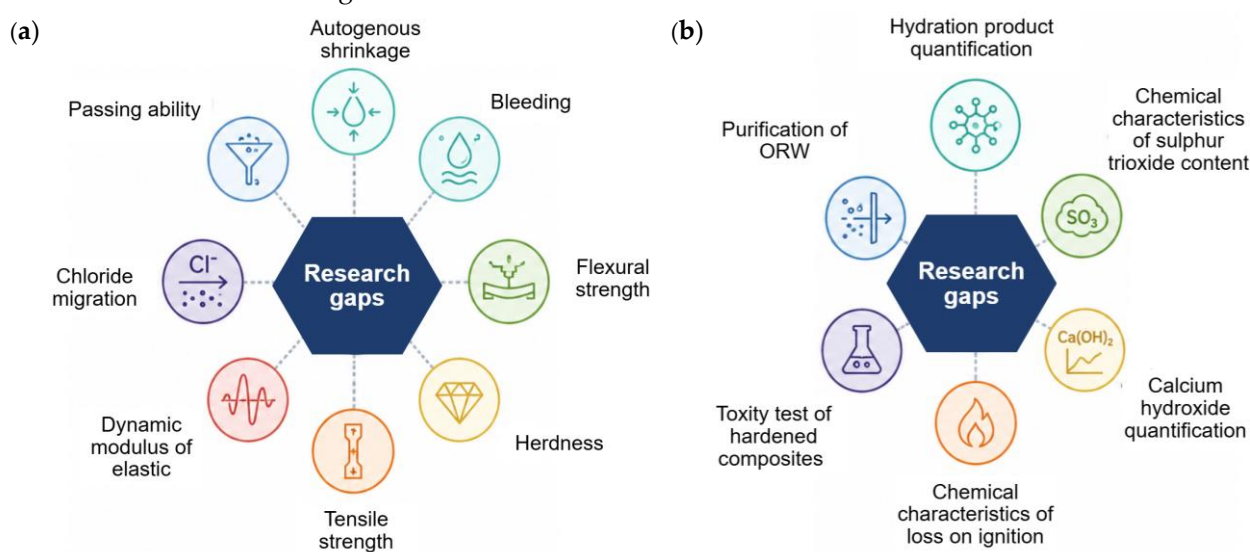


Figure 8. Research gaps in the case of research on rheological, physical, and mechanical properties of cement composites (a) and in the case of research on physicochemical properties (b).

5. Environmental and Economic Impact of REUSING of ORWs in Cementitious Composites

Currently, the situation in the global raw materials market is unstable, providing significant problems for companies due to their deficiency, inaccessibility, and rising costs. Simultaneously, as a consequence of daily and industrial activities, enormous quantities of waste materials are generated worldwide, which in many cases might be problematic and harmful [3]. To overcome these challenges, converting wastes or by-products into sustainable resource materials is found to be inevitably course of action. Without any

doubt, the following procedure is found to be in accordance with the latest trends and strategies, such as Cleaner Production, Sustainable Development, Green Chemistry, thereby providing a key opportunity to implement a circular economy. At present, this might be achievable by tackling waste management through the 5 Rs—reduction, recovery, recycling, reuse, and research [14]. Following this path, the recycling of ORWs in the construction sector might ensure numerous benefits for both industries and, ultimately, for our planet and health, which are generally listed in Figure 9.

Environmental safety is a key criterion for assessing the feasibility of using oil refinery waste in cement composites. Refinery waste, particularly spent FCC catalysts, may contain heavy metals, sulphur compounds, hydrocarbon residues, and coke deposits. Since their composition depends heavily on the quality of the crude oil, the degree of catalyst wear, and the refinery's operating conditions, each waste stream requires individual characterization before being subjected to a disposal process [44]. The incorporation of spent FCC catalysts into cementitious materials effectively reduces the mobility of contaminants by physically trapping them within the structure of the material and chemically stabilizing them within the cement hydration products. Environmental risk assessments based on TCLP tests have shown that the concentrations of heavy metals released from cement products containing spent FCC catalysts generally do not exceed permissible limits [45]. However, recent studies indicate that refinery waste should not be assessed solely on the basis of short-term leaching tests. Residues of heavy metals and process chemicals may continue to pose a threat to the environment under conditions of long-term exposure to atmospheric factors, carbonation, erosion, or following the demolition of a structure, which underscores the need to consider material durability in environmental assessments covering the entire life cycle of cement-based composites [46].

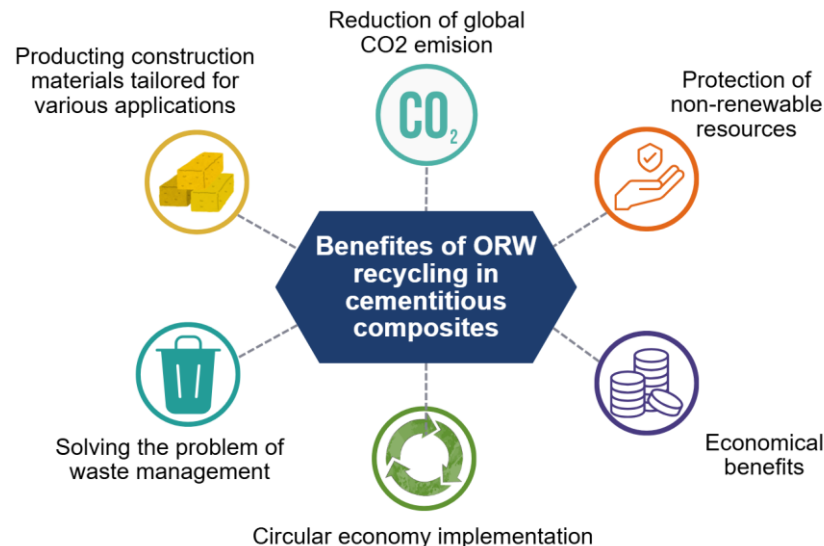


Figure 9. Benefits of ORW recycling in cementitious composites.

Accordingly, from the point of view of the petroleum industry, ORW disposal costs, and most notably, their environmental impact described in earlier sections, might be significantly reduced. Moreover, it is obvious that adding value to waste materials must also be a profitable business. From the point of view of the construction industry, the recycling of ORWs as partial cement or aggregate replacements will clearly reduce the manufacturing costs and the need for processing virgin resources in this sector, as well as the carbon footprint of final products. Moreover, such innovative products might also ensure better acceptance by end-users and customers in the global market (designers, engineers, constructors, and authorities).

The potential for cost and CO₂ emission savings is presented in Tables 5 and 6, respectively. The prices of resource materials, i.e., water, CEM I 42.5R Portland cement, and aggregates (0/2 mm, 2/8 mm, and 8/16 mm, respectively), necessary for manufacturing 1 m³ of concrete mix, were assumed based on generally available data. The emissions associated with concrete components assumed for the calculation are as follows: 0.9 kg CO₂/ton of water, 5.4 kg CO₂/ton of aggregates [47], and 712 kg CO₂/ton of cement [48]. A spent catalyst, as an example of ORWs, was assumed to be free of price and CO₂ emissions. The spent catalyst was treated as industrial waste that were already completed its primary life cycle in the refining process. Consequently, no environmental impacts associated with its production were attributed to it. Assuming a zero economic value for the catalyst should be considered a conservative assumption, since in practice refineries incur costs associated with its management or disposal [49]. Both economic and environmental calculations were performed for 1 m³ of concrete, in which cement was substituted with spent catalyst at replacement levels of 10% and 20% by mass and the results were compared with those of the reference concrete. It should be noted that transportation costs and emissions, as well as CO₂ emissions from the manufacture of the concrete mix, were not included.

Table 5. Economic benefits of utilizing ORWs (the Euro rate on 24 June 2026).

Ingredients	Control Mix			Cement Substitution		Fine Aggregate Substitution	
	Amount in m ³ of Concrete [kg]	Unit Price [€/tonne]	Price in m ³ of Concrete [€/m ³]	10%	20%	10%	20%
				Cost [€/m ³ Concrete]		Cost [€/m ³ Concrete]	
Water	175	1.16	0.20	0.20	0.20	0.20	0.20
Portland cement	310	209.3	64.90	58.40	51.9	64.90	64.90
Spent catalyst	0	0	0	0	0	0	0
Aggregate 0/2	715	18.6	13.30	13.30	13.30	13.30	13.30
Aggregate 2/8	445	18.6	8.28	8.28	8.28	8.28	8.28
Aggregate 8/16	717	20.9	15.01	15.01	15.01	12.00	10.60
		Σ	101.68	95.19	88.70	100.35	99.02
		Difference		6.49	12.98	1.33	2.66

Table 6. CO₂ emissions of concrete mixes.

Ingredients	Control Mix			Cement Substitution		Fine Aggregate Substitution	
	Amount in m ³ of Concrete [kg]	CO ₂ Emission [kg/tonne]	CO ₂ Emission in m ³ of Concrete [kg CO ₂ /m ³]	10%	20%	10%	20%
				CO ₂ Emission in m ³ of Concrete [kg CO ₂ /m ³]		CO ₂ Emission in m ³ of Concrete [kg CO ₂ /m ³]	
Water	175	0.90	0.16	0.16	0.16	0.16	0.16
Portland cement	310	712	220.72	198.65	176.58	220.72	220.72
Spent catalyst	0	0	0	0	0	0	0
Aggregate 0/2	715	5.4	3.86	3.86	3.86	3.47	3.09
Aggregate 2/8	445	5.4	2.40	2.40	2.40	2.40	2.40
Aggregate 8/16	717	5.4	3.87	3.87	3.87	3.87	3.87
		Σ	231.01	208.94	186.87	230.63	230.24
		Difference		22.07	44.14	0.38	0.77

The difference in costs and CO₂ emissions for the preparation of 1 m³ of concrete with the given substitution levels of cement and aggregate are graphically illustrated in Figure 10 a,b.

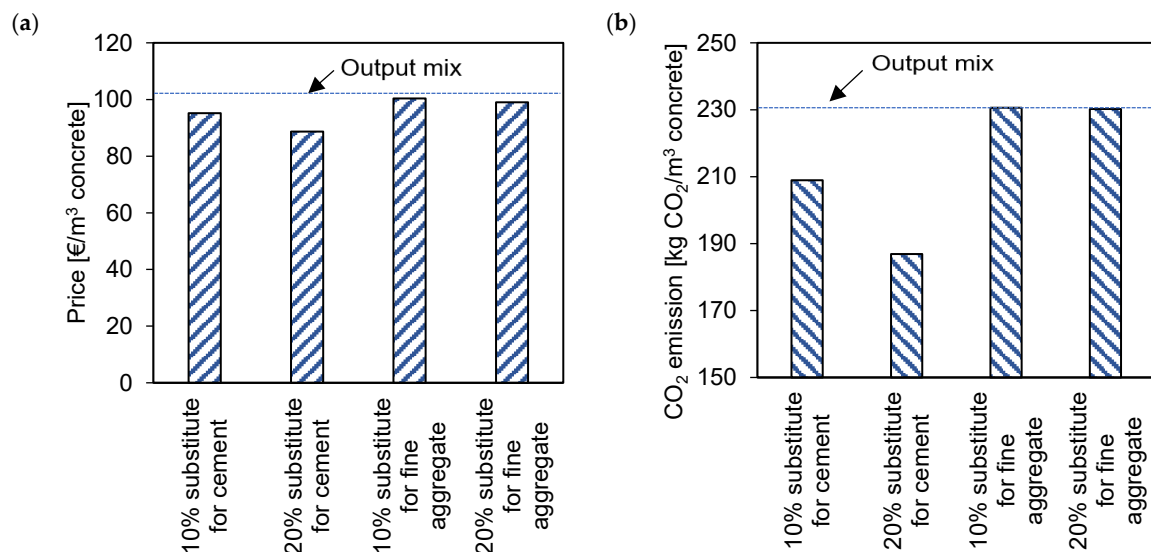


Figure 10. (a) Differences in the cost of the 1 m³ concrete mix (the Euro rate on 24 June 2026); (b) differences in the CO₂ emissions of the 1 m³ concrete mix.

Considering the above, as spent catalyst is a waste material which is considered to be free of cost and CO₂ emissions, while cement is the most expensive and CO₂-emitting component of a concrete, the greatest benefits in terms of cost savings and CO₂ emission reductions were obtained with its substitution. Overall, replacing 10% and 20% of cement offers resulted in the cost reductions of 6.49 and 12.98 €, respectively, as well as CO₂ emission reductions of 22.07 and 44.14 kg per 1 m³ of concrete, respectively. In the case of fine aggregate replacement, the corresponding values are 1.33 and 2.66 €, as well as 0.38 and 0.77 kg of CO₂ per 1 m³ of concrete, respectively.

6. Conclusions

Overall, the research interest regarding ORW recycling in cementitious composites has increased in recent years. On the basis of the conducted research review, the main conclusions and research directions might be drawn as follows:

- Various ORWs appear to possess huge potential to be recycled as sustainable resources in the construction sector, providing valuable environmental and economic benefits in both the construction and petrochemical sectors.
- Waste FCC catalysts derived from miscellaneous oil refinery plants revealed high pozzolanic activity, contributing to compressive strength enhancement of cementitious composites. Despite this, more extensive investigations carried out on resulting composites are recommended to clarify the complete impact of ORWs on their various properties, listed in the research gaps section.
- Apart from partial cement substitution, ORWs might also allow the replacement of a certain proportion of fine aggregate (sand) in mortar and concrete formulations. For this purpose, more research should be conducted. Nonetheless, such an application reveals less potential for both cost savings and CO₂ emission reductions.
- Considering the recycling feasibility of ORWs, the first step should be focused on investigating their complete properties. Such knowledge is invaluable, in terms of

understanding their impact on both freshly mix and hardened concrete. For this purpose, considering the variable characteristics of ORWs, an individual approach and more comprehensive analytical methods are recommended to be applied.

- ORW recycling in cementitious composites gives grounds to address the issue of environmental pollution with oil originated impurities, i.e., heavy metals, as they might be bound in the matrix of hardened composites. Moreover, chemical purification and activation of ORWs is found to be especially interesting as it might allow the valorization of ORWs, thereby contributing to the enhancement of their potential pozzolanic reactivity and mechanical properties of concrete as well as minimizing the risk of toxicity through the elimination of organic contaminants from their particles.
- An interdisciplinary approach and collaboration between researchers from various disciplines are highly preferable for the industrial implementation of ORWs in the construction sector.

Generally, four main research directions have been clarified, which are vital to be extended in the future. The topics present the perspectives for the future research activities that are planned to be conducted by the authors of the following paper:

- There is still huge room for exploration regarding the recycling of ORWs as both a cement substitute and a fine aggregate (sand) substitute in various types of cementitious composites, i.e., concretes and mortars, prepared with different formulations and conditions.
- Moreover, broadly understood chemical methods seem to be an interesting research trend, as they enable the purification of ORWs, thereby giving them additional value. Various analytical methods allow for the understanding of both the complete properties of ORWs and the performance of ORW-blended composites, which might be crucial in terms of their implementation possibility.
- Special effort should be made to determine the correlations between the performances of valorized and non-valorized ORWs using different methods, such as chemical oxidation and calcination, and the impact they provided to concrete especially in the case of the toxicity values, which is not known according to the literature.
- Artificial intelligence (AI) and machine learning (ML) offer compelling tools for optimizing the use of refinery waste in cement composites. By establishing predictive relationships between material properties, mix parameters, and composite performance, ML models can support mix optimization and reduce the need for extensive experimental testing. Similar approaches have recently been successfully applied in the field of construction materials [50,51].

Author Contributions: P.N., funding acquisition, project administration, supervision, and writing—review and editing; M.N., data curation, investigation, methodology, software, validation, visualization, and writing—original draft; M.C., data curation, investigation, methodology, software, validation, and writing—original draft; Ł.S., supervision and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was entirely funded by the project entitled “Experimental evaluation of influence of oil refinery waste materials used as a partial substitute of cement and natural aggregate on the properties of cementitious composite (MOR-CEM)”, supported by the National Science Centre, Poland (grant number: 2023/51/D/ST8/00601). For the purpose of Open Access, the author has applied a CC-BY public copyright licence to any Author Accepted Manuscript (AAM) version arising from this submission. This research was funded in whole by the National Science Centre, Poland, grant number: 2023/51/D/ST8/00601, entitled: “Experimental evaluation of influence of oil refinery waste materials used as a partial substitute of cement and natural aggregate on the properties of cementitious composite (MOR-CEM)”. For the purpose of Open Access, the author has applied

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Data Availability Statement: I declare that the data analysis presented herein was conducted independently, fairly, and in accordance with accepted statistical and/or analytical methods appropriate to the nature of the study. The data used in the analysis are from reliable sources, and have been properly prepared, cleaned and verified for completeness and consistency.

Conflicts of Interest: The authors declare no conflicts of interest.

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