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Innovative Concrete Modification Strategies: A Critical Review of Fibre Reinforcement, Polymer and Bio-Based Additives, Waste-Derived Materials, and Mechanical, Durability and Impact Performance

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Abstract: Concrete modification has evolved from a simplistic aim of maximizing compressive strength to a more complex objective of multifunctionality encompassing aspects such as crack prevention, toughness, impact resistance, self-repair and reduced resource consumption. This paper critically evaluates four groups of modification techniques - discrete fibers, polymer admixtures, biological (microbial) agents and recycled materials, paying special attention to the ways they influence the mechanics of concrete. Fibers work primarily in case of cracks formation and provide their mitigation via bridging and pullout effects, so they are especially effective in improving flexural toughness, residual strength and impact energy dissipation but not in terms of compressive strength. Films and interpenetrating networks formed by polymer admixtures increase adhesion and tensile properties, however an excessive amount of polymers, air entrainment and inappropriate curing conditions reduce compressive strength. Microbial additives may promote calcite precipitation sealing fine cracks; their impact on the strength of concrete is relatively small and depends on the survival rate of bacteria in an alkaline environment. The comparative matrix along with a decision tool is provided, where the target property is associated with the right modification along with the fewest tests required to prove an impact claim. It is concluded that there is no one additive that enhances all properties; interaction effects in hybrid systems need to be tested factorially; and rate sensitivity is essential for any impact claim test.

Keywords: Fibre-reinforced concrete; Polypropylene fibre; Polymer-modified concrete; Microbially induced calcite precipitation; Waste marble; Impact resistance; Multi-performance design.

I. INTRODUCTION

The use of concrete is more prevalent in the world of construction because it is economical, moldable, and resistant to compressive forces. However, the shortcomings associated with it are also quite famous; these include low strain capacity under tension, brittle nature, porous structure, which leads to the penetration of moisture and aggressive ions, and high carbon content in concrete, which is mainly due to Portland cement clinker [1]. During the last fifty years, there has been considerable research done to improve upon these properties of concrete.

Modification methods tend to be considered independently; fibre scientists rarely talk to polymer experts, while bacteria-based curing became a separate field that emerged without direct reference to concrete. Nevertheless, a designer faced with a choice of mixtures for industrial flooring, repair, or protecting walls has to evaluate these alternatives relative to the same criteria of performance. A crack-controlling fibre, a polymer which provides better bonding, a bacterium that seals cracks, and a mineral from a waste stream, replacing some of the cement, operate by completely different principles, and their advantages are not substitutable. That is why the purpose of this review is both comparative and mechanistic. Section 2 describes the process of selecting the literature for analysis. Sections 3-6 discuss fibre reinforcement, polymer modification, bio-based additives and waste-based minerals, respectively, concentrating on mechanical behavior and the conditions influencing it. Section 7 compares the four techniques and considers hybrids of them. Section 8 suggests criteria for choice and testing, while Section 9 indicates areas where research is still needed.

II. REVIEW APPROACH

This is a critical narrative review and not a systematic review or a meta-analysis. Relevant papers from peer-reviewed journals and reviews were selected by searching through Google Scholar and Scopus-indexed journals using a combination of keywords like fibre-reinforced concrete, polymer modified concrete, latex, bacterial healing, calcite precipitation, waste marble, recycled aggregates and impact resistance. Preference was given to (i) comprehensive reviews which lay down the existing state-of-the-art, (ii) experimental works which focus on the mechanism of impact energy absorption and not just the strength values and (iii) recent studies from the year 2020 onwards which build on the previous findings. The studies were rejected in case it was not possible to cross verify their bibliographic information or digital object identifiers. In view of the varied mixture ratios, dimensions and testing standards, numerical comparisons are avoided.

III. FIBRE REINFORCEMENT

A. Mechanisms

The role of fibres before cracking of the matrix is negligible. When a crack develops, the fibres intersecting the crack take up the tensile load and release energy due to debonding, pull-out, and for certain types of fibres, breakage [2]. It leads to the transition from abrupt brittle failure to gradual failure accompanied by energy dissipation. That is why the greatest impact of fibres can be observed in flexural toughness, residual flexural strength, crack width reduction and energy absorption from impacts, whereas the influence on compressive strength is insignificant and even negative at high fibre content [4].

The performance of fibres depends on their material, length, aspect ratio, surface roughness, volume fraction, orientation and matrix properties. Microfibres of short length are useful for combating plastic shrinkage cracking in fresh concrete, macrofibres are responsible for the residual structural capacity of hardened concrete, and steel fibres have a high modulus and mechanical anchorage due to their hooked or notched shape [2, 4]. Natural fibres of sisal and jute are characterized by a low embodied energy but sensitivity to moisture and require surface protection from alkalinity of the matrix [4].

B. Polypropylene fibres

Polypropylene (PP) fibers are favorable since they are light weight, chemically inert, not susceptible to corrosion and economical. According to recent systematic review, evidence about improved splitting tensile and flexural properties and crack resistance was established by research studies using low to moderate amounts of PP fibers; however, high doses may suffer from reduced workability and poor fiber dispersion [5]. In the same systematic review, improved shrinkage crack resistance and some aspects of durability were noted and these findings align with general findings related to durability of PP fibers [6].

The main limitations of PP fibres are their low elastic modulus and hydrophobic surface. A low modulus means that PP microfibres bridge cracks effectively only at small crack openings, while the weak fibre–matrix bond limits stress transfer. Surface treatments, fibrillated geometries and hybridisation with stiffer fibres have been proposed to address these issues. In practice, PP fibre content should be optimised against slump retention, compaction and the required failure mode rather than maximised.

C. Impact behaviour

Impact performance is a separate discipline. High strain rates cause the rise of the concrete strength and change of cracking and energy absorption, which is dependent on fiber pull-out processes [7, 8]. Reviews of impact performance demonstrate that fibers decrease spalling and scabbing, increase the onset of perforation and the number of impacts until failure in drop-weight tests [7, 8]. Nevertheless, the test methods vary from drop-weight, Charpy type, projectile, split-Hopkinson-bar tests and impose different rates and boundary conditions; so, the results obtained in various papers cannot be compared directly [7]. Moreover, Esaker et al. emphasize that empirical formulas for penetration are still questionable for fiber-reinforced concrete [8].

Structural performance of RC elements in blast is dependent on the weight of the charge, the stand-off distance and angle of incidence as well as on the material properties as it was demonstrated in explicit dynamics analysis of RC frames [9]. So, the improvement of the material is necessary but insufficient proof of blast performance – the mixture showing good performance in drop-weight test should be analyzed at member/frame level under the certain threat..

IV. POLYMER MODIFICATION

A. Mechanisms

Polymer admixtures—latexes such as styrene–butadiene rubber (SBR), acrylic emulsions, epoxy systems and polyvinyl acetate (PVAc) dispersions—modify concrete by forming continuous films or interpenetrating networks within the hydrating cement paste.

Ohama's classical description treats polymer-modified mortar and concrete as a co-matrix in which cement hydration and polymer film formation proceed together [3]. The films bridge microcracks, seal part of the capillary pore system and improve adhesion to aggregates and substrates. Fowler noted that, despite decades of research, polymer concretes have remained niche products mainly because of cost and a lack of design guidance, rather than because of technical shortcomings [10].

B. Mechanical effects

The result is increased tensile and flexural strength, increased adhesion, and increased flexibility, along with a slight decrease in compressive strength and modulus of elasticity. Aggarwal et al. discovered that both epoxy and acrylic emulsions enhanced the flexural strength, bond, and water resistance of mortars, where the effect was dependent on the polymer-to-cement ratio and curing process [11]. There are three reasons why there is a reduction in compressive strength, as follows: (a) Polymers have an air-entraining effect, (b) They retard the hydration process, and (c) They need time for dry curing to develop film, which is opposed to the wet curing process of cement.

C. Adhesive-type PVAc additives

Sometimes, commercially available PVAc-based adhesives are employed at the construction site as economical bonding materials. Kudoli performed experiments involving the use of Fevicol, a type of PVAc-based adhesive, in concrete mixes and observed the effect of workability and strength with varying dosages [12]. While such researches provide some practical information, the findings cannot be extrapolated for all types of polymer additives. PVAc is susceptible to moisture, and the hydrolysis process is accelerated by alkali. Commercial PVAc products vary in content of active substance, plasticizers, and fillers. The future experiments should provide chemical structure of polymer along with solid content instead of trade name, control mixtures and service conditions.

D. Where polymers are most useful

Because polymer modification trades a small amount of compressive strength for better adhesion, flexibility and lower permeability, it suits thin overlays, patch repairs, bonding layers and precast elements exposed to aggressive environments better than mass structural concrete.

V. BIO-BASED ADDITIVES

A. Microbially induced calcite precipitation

Modification of a bio-based type utilizes microorganisms, specifically those which can tolerate alkalinity and form spores such as *Bacillus*. These microorganisms precipitate calcium carbonate when exposed to water and nutrients which enter through the cracks. This approach was proven by Jonkers et al., who demonstrated that the bacterial spores can be sustained within the concrete and can precipitate the calcite within the cracks [13]. De Muynck et al. have reviewed the broader applications of the microbial carbonate precipitation within construction materials [14].

B. Effects on mechanical properties

The main purpose of bacterial additives is crack sealing, but they also influence strength. Guddad et al. incorporated *Bacillus subtilis* in concrete and reported improvements in compressive strength and chemical durability compared with control mixtures, which they attributed to calcite filling pores and microcracks [15]. Other studies report smaller or inconsistent strength changes, depending on bacterial dosage, nutrient type and the carrier used [16]. Broader reviews of self-healing cementitious materials place bacterial healing alongside autogenous healing, encapsulated polymers and shape-memory systems, and stress that the healing mechanism should be chosen to suit the expected crack width and exposure [17, 18]. Nutrients such as calcium lactate and yeast extract can retard hydration, so strength gains are not guaranteed.

C. Carriers and limitations

Bacteria added directly to the mix face high pH, shrinking pore space and mechanical damage during mixing. Encapsulation in silica gel, polyurethane, expanded clay or other carriers improves survival; Wang et al. showed that bacteria immobilised in silica gel or polyurethane could precipitate calcite in cracks, and that the choice of carrier strongly influenced healing efficiency [19]. Carriers, however, add cost and can reduce strength if they act as weak inclusions. Healing is generally limited to crack widths below roughly 0.5 mm and requires moisture. Crack closure at the surface should therefore not be equated with recovery of stiffness or load capacity, a point that becomes critical when bio-based concrete is considered for structural repair.

VI. WASTE-DERIVED MATERIALS

A. Waste Marble

The treatment of marble results in the production of high amounts of powder and larger fragments. As a substitute for cement, marble powder is used as a filling material and nucleation center, while as a substitute for sand, it influences grading and particle packing. According to Aliabdo et al., it is possible to use marble dust for partial replacement of sand without considerable reduction of the strength of concrete, whereas the replacement of cement was not advantageous due to dilution of the reactive binder [20]. According to Ergün, partial replacement of sand and cement with the mixture of diatomite and waste marble powder was accompanied by maintenance or improvement of the compressive strength of concrete [21]. As an alternative to coarse aggregates, marble aggregates may be used as well; according to Hebhoub et al., the partial substitution of natural aggregates with marble aggregates up to about 75% yielded good mechanical performance of concrete [22].

Sathe et al. examined waste marble both as partial cement replacement and as partial fine-aggregate replacement and assessed mechanical, durability and microstructural properties [24]. Separating the two replacement routes is important: improvements attributed to “marble” may come from better packing in the aggregate role, while losses may come from dilution in the binder role. Studies that report only a total “marble content” cannot distinguish these effects.

B. Recycled aggregates and supplementary materials

The recycled concrete aggregate material helps in reducing the usage of quarried stone but they have adhering mortar and it makes water absorptivity high and reduces the density and strength of the material. Silva et al. classified the properties of the recycled aggregate according to the material content and suggested the classification of the material based on the constituent materials [25]. Turk et al. discussed various types of waste material used in the concrete mix design and suggested that the performance of waste material is dependent upon the process and replacement ratio and also the modification of the mix design like presaturation of supplementary cementitious materials [26]. Generally speaking, largest reduction in CO₂ comes from the replacement of clinker by the reactive material such as calcined clay, slag and fly ash and not by the use of inert fillers [1].

C. Requirement of characterisation

There are different waste materials depending upon the source and process. A good study will include particle size distribution, specific gravity, water absorptivity, chemical composition and deleterious composition such as sulphates and organics wherever applicable [26].

VII. COMPARATIVE ASSESSMENT AND HYBRID SYSTEMS

Table 1 compares the four strategies by mechanism, typical mechanical effect, practical dosage window and main risk. Table 2 summarises the direction of their effects on key properties.

Table 1. Comparison of concrete modification strategies.

Strategy	Primary mechanism	Typical mechanical effect	Practical dosage window	Main risk
PP / synthetic fibres	Crack bridging, pull-out	↑ flexural toughness, residual strength, impact energy; ≈ compressive strength	~0.1–0.5% by volume (micro)	Loss of workability, clumping, weak bond
Steel / macro fibres	Anchored bridging	↑↑ toughness and post-crack capacity	~0.5–2% by volume	Corrosion at surface, cost, balling
Polymer admixtures	Film formation, adhesion	↑ flexural strength, bond, deformability; ↓ slight compressive strength	~5–20% polymer–cement ratio	Air entrainment, curing sensitivity, cost
Bacterial (MICP)	Calcite precipitation	≈ to slight ↑ strength; crack sealing	Product-specific; spores + nutrients	Bacterial survival, nutrient retardation, crack-width limit
Waste marble / fillers	Packing, nucleation	≈ or ↑ at low levels; ↓ at high cement replacement	~5–10% of cement; higher for sand	Dilution, source variability
Recycled aggregate	Aggregate substitution	↓ modulus and strength at high levels	Up to ~30% coarse aggregate common	Absorption, adhered mortar

Table 2. Direction of effect on key properties ($\uparrow$ improves, $\approx$ little change, $\downarrow$ may reduce; effects depend on dosage and mix design).

Property	Fibres	Polymers	MICP	Waste marble
Compressive strength	$\approx$	$\downarrow$ to $\approx$	$\approx$ to $\uparrow$	$\approx$ (low), $\downarrow$ (high)
Flexural / tensile strength	$\uparrow$	$\uparrow$	$\approx$	$\approx$
Toughness and impact	$\uparrow\uparrow$	$\uparrow$	$\approx$	$\approx$
Crack sealing	—	$\approx$	$\uparrow\uparrow$	—
Workability	$\downarrow$	$\uparrow$ to $\approx$	$\approx$	$\approx$ to $\downarrow$
Resource efficiency	$\approx$	$\downarrow$	$\approx$	$\uparrow$

Hybrid systems are attractive because the strategies are largely complementary: fibres control crack width, bacteria can seal the narrow cracks that fibres leave, and fine waste powders can densify the matrix around fibres. Yet combinations can also interfere. Fibres reduce workability, which may be worsened by fine powders that increase water demand; polymers entrain air that reduces strength; and nutrients for bacteria can retard hydration. These interactions mean that the performance of a hybrid mixture cannot be predicted by adding the effects of individual additives. Factorial or response-surface experimental designs are needed to separate main effects from interactions.

The same considerations apply to performance that goes beyond static strength. Freeze–thaw resistance, for example, depends on air-void structure and saturation, and studies on sustainable concrete show that modification can either improve or worsen frost resistance depending on how it alters pore structure [27]. Data-driven models can help screen candidate mixtures before testing, provided they are trained on representative data and validated on independent mixtures [28, 29].

VIII. A FRAMEWORK FOR SELECTING AND SUBSTANTIATING MODIFICATIONS

Figure 1 summarises a selection logic based on the property that governs design. The starting point is the performance requirement—crack control, impact resistance, adhesion, crack sealing or resource efficiency—rather than the additive. For each requirement, the framework identifies the most effective modification and the minimum evidence needed to support a claim.

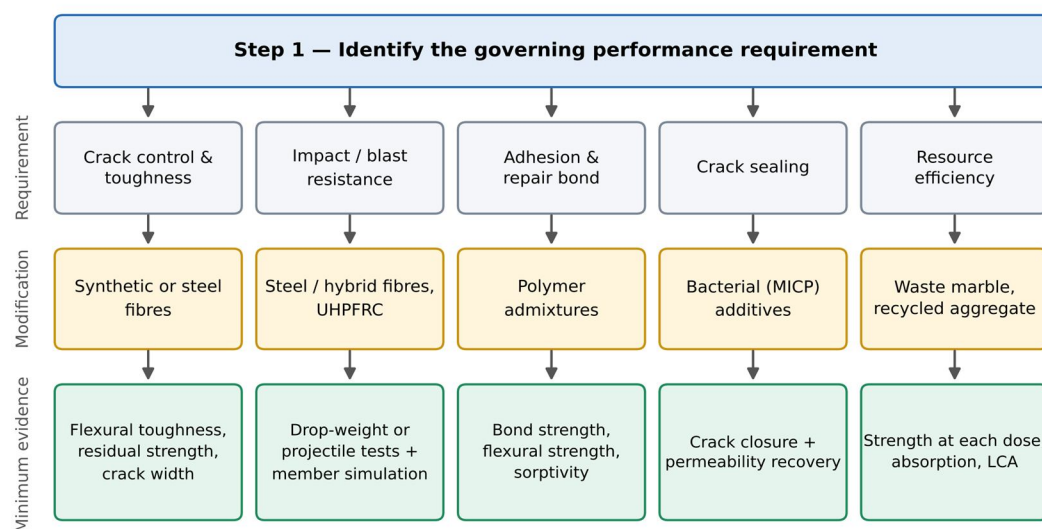


Figure 1. Selection framework linking the governing performance requirement to the modification strategy and the minimum supporting tests.

Three principles follow. First, the test programme should match the claim: a fibre mixture claimed to improve impact resistance should be tested under impact, not judged by compressive strength. Second, every modified mixture needs a matched control with the same water–binder ratio, curing and age. Third, a balanced profile—fresh properties, compressive, tensile and flexural strength, at least one durability indicator, and microstructural evidence—should be reported so that improvements in one property are not achieved at the hidden cost of another.

IX. RESEARCH GAPS

These five gaps can be highlighted. (i) The majority of studies reveal a property at once; balanced systems comprising fresh, mechanical, durable and dynamic performance characteristics are very uncommon. (ii) There is no unified method for conducting impact tests, thus comparison among fibre types and dosages becomes impossible. (iii) Biodegradable systems do not have the data on the multiple self-repair process and mechanical strength recovery in realistic moisture environments. (iv) Waste-based systems require material-specific analysis of life cycle. (v) Hybrid systems are scarcely explored using factorial experiments.

X. CONCLUSIONS

- 1) Fibres act after cracking. Their main benefits are flexural toughness, residual strength, crack-width control and impact energy absorption; compressive strength changes little. Polypropylene fibres are most effective at low volume fractions, typically up to about 0.5%.
- 2) Polymer admixtures improve adhesion, flexural strength and deformability but often reduce compressive strength slightly. They suit repairs and overlays better than mass structural concrete, and results for one commercial product, such as a PVAc adhesive, should not be generalised.
- 3) Bacterial additives can seal fine cracks and may modestly improve strength, but bacterial survival, nutrient effects and crack-width limits restrict their reliability. Crack closure is not the same as recovered load capacity.
- 4) Waste marble and recycled aggregates conserve resources. Moderate replacement is usually acceptable, but the replacement route (binder or aggregate) and source variability determine performance.
- 5) No single strategy improves every property. Selection should start from the governing performance requirement, use matched controls and rate-appropriate tests, and treat hybrid systems as interacting rather than additive.

A. CRediT authorship contribution statement

- Shreyash Bhapkar: Investigation, Data curation, Visualization, Writing – original draft.
- Anand B. Kudoli: Conceptualization, Methodology, Supervision, Validation, Writing – review and editing.

B. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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D. Data Availability

No new data were generated in this review. All information discussed is available in the cited literature.

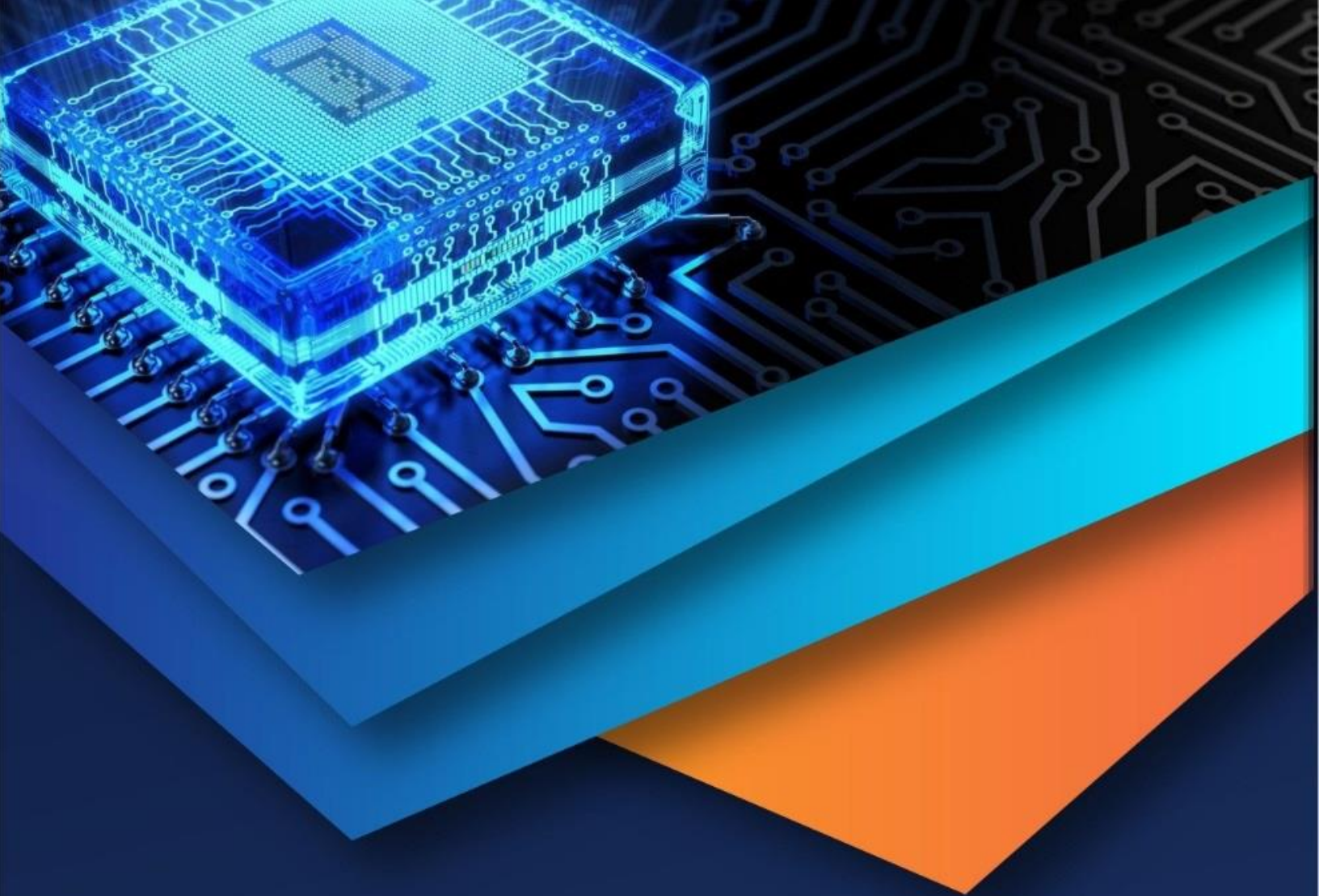
E. Declaration of generative AI use

During the preparation of this work, the authors used ChatGPT solely for language editing and grammar checking. After using this tool, the authors reviewed and revised the content as necessary and take full responsibility for the content of the publication.

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