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CRITICAL REVIEW ON PROJECT PERFORMANCE EVALUATION OF NANO ZEOLITE USING LIFE CYCLE ASSESSMENT AND COST–BENEFIT ANALYSIS

Devdeepkumar Patanvadiya[1]*, Vanshika Jingar[2]*, Karan Chauhan[3]*

1 M.Tech Scholar, Department of Civil Engineering, Parul University, Vadodara, India
2 Assistant Professor, Department of Civil Engineering, Parul University, Vadodara, India
3 Assistant Professor, Department of Civil Engineering, Parul University, Vadodara, India

Abstract

Nano zeolite is a nanoscale aluminosilicate material with a high surface area, a porous structure, a high ion-exchange capacity, and surface reactivity. Because of these properties it has attracted growing interest in the fields of construction, soil stabilization, asphalt mixtures, geopolymer systems and environmental applications. The present review looks at the literature concerning the evaluation of nano zeolite's project performance, with a special focus on its mechanical performance, durability, environmental sustainability, life cycle assessment (LCA), life cycle cost and cost–benefit considerations. The studies reviewed show that both zeolite and nano-zeolite are able to increase strength and promote densification in certain construction applications and can in part substitute conventional cementitious or filler materials. For instance, recent studies have found that the performance of cement-zeolite sand can be improved within certain optimal replacement ranges and that there is a significant increase in strength in soft soils treated with nano-zeolite and with municipal solid waste incineration ash. A recent study on asphalt also found that a 50% substitution of cement filler with nano-zeolite represented the best level for Marshall performance under the laboratory conditions stated. At the same time, studies based on life cycle assessment indicate that the environmental benefits are highly dependent on material production, energy consumption, the use of alkali, transportation, the replacement ratio and the definition of the system boundaries. The literature makes it clear that there is a need for an integrated project-level evaluation that combines technical performance, life cycle assessment and economic analysis rather than looking at these aspects separately. The review thus suggests an integrated framework for assessing nano zeolite in comparison with conventional stabilizers such as cement and lime by means of performance

indicators, environmental impact categories and cost–benefit indicators.

KEYWORDS: NANO ZEOLITE; SOIL STABILIZATION; SUSTAINABLE CONSTRUCTION; LIFE CYCLE ASSESSMENT; COST–BENEFIT ANALYSIS; PROJECT PERFORMANCE; CEMENT REPLACEMENT; ASPHALT FIL

Introduction

The building industry is now calling for materials which are able to meet engineering performance standards while at the same time lowering their environmental impact and overall life costs. Although conventional building materials, especially those based on cement, can offer high strength and reliability they are linked with high energy use and emissions of greenhouse gases. As a result, research is focusing on supplementary, waste-derived and mineral-based materials which can decrease the need for conventional materials.

Zeolites are porous aluminosilicate materials which have a number of established uses in the areas of adsorption, ion exchange, catalysis, agriculture, water treatment and construction. A review by Kordula and Wyszkowski has summarized the properties of zeolites, the methods of their synthesis and their applications, pointing out their wide practical relevance. At the nano scale the higher surface-area-to-volume ratio can lead to increased surface interactions and reactivity, although the real engineering benefit will vary according to the characteristics of the particles, the dosage, the composition of the matrix and the processing conditions.

The range of research on nano zeolites covered in this dissertation has now gone beyond its use in environmental applications to include concrete, soil stabilization, asphalt and geopolymer systems. According to the literature review of papers contained in the dissertation, there is a consistent trend whereby a large number of the studies focus on strength, durability and material properties, while a considerably smaller number of them incorporate life cycle assessment, cost–benefit analysis and evaluation of project-level performance.

1. Review Methodology

The review has been prepared using the literature collected for the MTech dissertation, supplemented by verification of certain publications through the publishers or via scholarly records. The collection of sources covers research on the synthesis of nano-zeolites, zeolite properties, soil stabilization, the substitution of asphalt fillers, zeolite-based geopolymers, life cycle assessment (LCA) and the economic evaluation over the product's life cycle. The papers were divided into five themes: (I) material characteristics and synthesis, (ii) construction and geotechnical applications, (iii) environmental performance and LCA, (iv) economic performance, and (v) research gaps relevant to an integrated project evaluation.

The review is mainly narrative and analytical not a statistical meta-analysis; it only includes numerical results when the sources in question give specific values and does not regard laboratory findings as direct proof of performance at field scale.

2. Nano Zeolite: Properties and Characteristics

Zeolite consists of a three-dimensional Alumni

(Placeholder1)silicate framework containing interconnected pores and exchangeable cations. The combination of porous structure, adsorption capacity and ion-exchange behavior gives zeolite a wide range of applications. The literature used in this dissertation describes nano-zeolite particles in the approximate 1–100 nm range, while the 2026 soft-soil study used particles reported at approximately 30–50 nm.

Important properties for construction applications include specific surface area, particle size, chemical composition, surface charge, water demand, cation exchange capacity and pozzolanic/reactive behavior. These properties can influence particle packing, hydration or pozzolanic reactions, interfacial bonding and pore structure. However, high surface area may also increase water demand and can make dispersion and dosage control more important.

3. Applications of Nano Zeolite in Construction

4.1 Soil Stabilization

This application presents an opportunity for nanomaterial use on soil stabilization since its small particle size allows interactions with soils minerals despite having a relatively lower dosage. A literature review conducted by Kumar et al., demonstrated the incorporation of Municipal Solid Waste Incineration Ash (MSWIA), a nano-zeolite, into Soft-Soil improved its 1-day UCS values up to 300kPA when dosed at 20% MSWIA & 1% Nano-Zeolite.

However, this treated sample experienced higher increases in subsequent testing periods reaching 18.67% and 34% respectively compared to its initial 1-Day UCS levels after curing times of seven and twenty-eight days. Moreover, this improvement was attributed to the resultant dense matrix formed as observed through Scanning Electron Microscopy (SEM) tests alongside elemental identification of Si, Al, Ca & Fe derived from the reaction product via Energy Dispersive X-ray analysis (EDX).

Unfortunately, results displayed a direct correlation between incrementing dosages of both the MSWIA and Nano Zeolites regarding optimum moisture contents while simultaneously experiencing decreased Maximum Dry Densities which may influence planning decisions during project execution.

4.2 Cement–Zeolite Improved Sand

In their work Nasrullah et al. used unconfined compression tests (UCC), LCA and AI based Mult objective optimisation to investigate Cement-Zeolite improved sands.

They found that there was an optimal Zeolite range (approximately 30 – 45%) under the investigated conditions for improving strengths, costs and environmental impacts. Their results highlight how important optimisation is as increasing cement replacement is not always beneficial since this may lower the strengths if too much Zeolite is added.

4.3 Asphalt Mixtures

Nano zeolite has been assessed as potential filler material substitute into asphalt concrete (AC) wearing course mixture by Ismay et al. They evaluated 0%, 25%, 50%, 75% and 100% substitution of Nano-zeolite with respect to cement filler materials using the optimal Asphalt Content of 6.04%.

The report indicated that the best point is obtained through 50% Substitution providing Marshall Stability value of 1,235.87kg with Marshall quotient of 404.52kg/mm. Also, they showed that the VIM, VMA, and VFA values are given as 3.18%, 15.68%, and 79.58% respectively. Further evaluation for rutting, moisture damage, aging effect, and field performances is recommended.

4.4 Zeolite-Based Geopolymers

As well as their applications in cementitious composites, the incorporation of zeolites into low carbon constructions has attracted interest recently. In particular, investigation on use of zeolites for development of geopolymer (lower carbon) composites with other industrial by-products such as blast furnace slag are ongoing.

Amari et al., investigated production of zeolite based geopolymer composites incorporating blast furnace slag and assessed the engineering properties together with an LCA.

The results showed that the zeolite composites achieved a maximum mechanical strength of ~40MPa while presenting various environmental advantages when compared with conventional concrete.

4.5 Environmental Applications

A nano-zeolite has been produced by Ghadban et al. for use in the removal of methylene-blue from wastewater (Ghadban et al., 2013). Characterisation results obtained via XRD and AFM have indicated that their particles have a diameter around 95nm .

This illustrates the far greater extent to which the properties of nanotechnology can apply towards more broadly sustainable outcomes, albeit without implying a direct correlation between success in the remediation of environments and building performance.

4. Life Cycle Assessment of Zeolite and Nano Zeolite

The Life Cycle Assessment (LCA) methodology allows us to quantify all environmental impacts occurring during the various stages of a certain product's lifecycle, including the raw-material extraction phase, production, transport, use and end-of-life, depending on the defined system boundary. In this case, we need to account for several aspects when conducting the LCA of nanoscale zeolites used in construction applications such as their source, synthesis/processing, drying, grinding, energy usage, chemical inputs, transport, integration within the construction material and ultimately their service life and end-of-life.

A research group led by Grimaldi applied an LCA approach to investigate both the environmental implications of continuously-flowing zeolite A production relative to standard batch production. By doing so they found that the degree of benefit derived from the application of process intensification varied with respect to each specific impact category examined and process configurations, which could prove relevant for nano-zeolite materials since their performance against other alternative materials needs to be evaluated on multiple fronts beyond simply replacing cement content. Moreover, they also identified NaOH production as a significant contributor toward overall environmental impact resulting from their particular synthesis route, thereby emphasizing how crucial it becomes to evaluate our unique manufacturing pathways before labelling one product over another as inherently "better".

To demonstrate some practical examples where integrating material evaluation techniques along with LCA analyses proved beneficial, Amari et al performed extensive studies related towards developing novel types of geopolymers based upon various kinds zeolites.Meanwhile Nasrullah & colleagues went even further incorporating elements dealing directly concerning structural integrity improvement, while maintaining consideration given towards potential costs incurred alongside respective reductions witnessed pertaining towards negative externalities generated throughout entire duration involved creating these innovative substances .

5. Cost–Benefit and Life-Cycle Economic Considerations

Should Cost-Benefit Analysis (CBA) show that the additional/reduced costs related to nano-zeolite usage is justified by the beneficial effects over the project lifetime? These might include, but are not limited to:

nano-zeolite purchase /synthesis cost transportation storage mixing and dispersion water required equipment quality control changes in construction times benefits from using nano-zeolite: reduction in consumption of cement/lime improvement of strengths lower maintenance needs better durability reduction in quantity of materials used environmental benefits which could be monetised if there's an appropriate valuation methodology already in place

In addition to the above considerations, when doing a project level economic evaluation, we recommend not just looking at initial cost of materials but also factoring in potential savings in terms of alternative stabilisers usage (e.g. soil stabilisation projects), or extra material processing/transport/water use, etc. There have been studies on the utilisation of zeolite as a partial substitute to traditional cementitious stabilisers – this has been shown to improve durability while decreasing the overall cost and emissions. They found that an approximate optimum would occur at around 30% zeolite replacement given the parameters they looked at.

6. Integrated Project Performance Evaluation

A multi-criteria framework for evaluating the introduction of nonelite into construction projects management that consists of 4 groups (technical, environmental, economic and project/resource) could be considered as an appropriate one

Performance group	Key indicators	Possible comparison	Project relevance
Technical	UCS, Marshall stability, durability, swelling, density	Nano zeolite vs. cement/lime	Quality and service life
Environmental	CO_2, energy, water, resource use, waste	LCA per functional unit	Sustainability
Economic	Initial cost, LCC, CBA, NPV/BCR where applicable	Alternative materials	Budget and value
Project/resource	Material quantity, construction time, water demand, maintenance	Alternative construction methods	Time and resource efficiency

An important aspect of this example is that 'functional unit' needs to be taken into account. A comparison based solely on price per kilogram may have limited utility – for instance when considering how well different materials are suitable for use as stabilizers of soil.

For example, if we compare two technologies for producing an equivalent length of treated road surface (soil stabilized) then a better definition of 'functional unit' would be 'one square metre of road sub-grade at a defined depth with certain performance characteristics. Similarly, if assessing the production of a given quantity of asphalt (asphalt concrete wearing course) then the functional unit might be expressed in terms of tonnes of AC-WC mixture which meets particular performance criteria. It will also allow us to make comparisons between the various technical, environmental and economic outcomes.

7. Research Gap

The first key area for further investigation would be to address the fact that much of what has been published to date relates to nanoscale properties (strength/durability) as opposed to whole project level properties.

The second area is related to life cycle assessment studies being sparse when compared with more generalised mechanical performance studies. This may highlight an issue that could be addressed by undertaking more cost-benefit analyses which have thus far proven to be quite uncommon. In addition, there seems to be some scope to incorporate both Life Cycle Analysis and Cost Benefit Analysis into one overarching decision-making process.

Thirdly, given that most applications focus at a field scale and over a period of time, perhaps attention is needed to address the limitations regarding field scale validation and data about longer term durability. Another key area to consider is the distinction between using natural vs. synthetic vs. nano-zeolites – this difference extends through their production routes and affects various parameters such as particle sizes, costs etc. Future work needs to make sure that all of these factors are included and clearly stated in publications so as to ensure that they are adequately covered.

8. Proposed Framework for the Present Study

The proposed framework derived from the review of literature will include 9 major steps as listed below:

- Characterize Nano-zeolite,
- Identify the selected construction application,
- Determine the Optimum Dosage by Laboratory Performance Testing,
- Define Functional Unit and System Boundary,
- Perform LCA for both Nano-zeolite & Conventional Alternative,
- Estimate Initial & Life-Cycle Cost,
- Conduct CBA with Measurable Project Benefits,
- Compare Alternatives using Technical, Environmental and Economic Indicators,
- Develop Decision Framework to Facilitate Adoption into Construction Projects.

In addition to the above-mentioned principles, it will also ensure that optimum nano-zeolite percentage can only be decided based on combined performance parameters instead of one particular strength parameter, and finally decide if this material meets necessary requirements regarding its ability to satisfy a desired trade-off between different important attributes such as engineering performance, environment impact, project cost and resources efficiency

9. Conclusions

A review of available literature confirms the great promise offered by nano-zeolite and related zeolite-based materials towards the goal of more sustainable construction materials via soil stabilization, cement replacement, asphalt filler system improvements and the development of geopolymers. The high surface activity combined with the porous aluminosilicate matrix enhances their ability to interact with other materials provided adequate amounts are used.

However, this review has shown how critical the importance of identifying what levels will ensure optimal functionality across different applications. It was found that, although optimum levels were identified in all case studies, they differ considerably between cemented sand, soft soil and asphalt systems, preventing the identification of a general-purpose nano-zeolite dosage recommendation based on current studies. To truly verify the benefit offered to the environment by using nano-zeolite as part of a sustainable strategy requires verification of impact via LCA. As the impacts generated through synthesis, chemicals involved, use of energy and transport activities may negate many benefits realized by replacing traditional materials.

Therefore, the greatest contribution possible during the course of this MTech dissertation would involve the combination of technical performance (in terms of effectiveness), LCA and cost/benefit assessment within one unified evaluation framework aimed specifically at individual projects.

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