Review on NSM-CFRP Method for Enhancing Shear Capacity in Reinforced Concrete Deep Beams

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Abstract. The demand for improved strengthening techniques for current concrete structures is on the rise. Many structures that will still be in use two decades from now have already been constructed. A portion of these structures must undergo enhancements or be replaced, as they are deteriorating not only from natural processes but also from mistakes made during their design and construction. Near-surface mounted (NSM) utilizing Fiber-Reinforced Polymer (FRP) bars has proven to be a successful method in enhancing the flexural and shear performance of both existing and new Reinforced Concrete (RC) elements. This technique is considered innovative and rapidly developing, attracting significant attention from researchers. Therefore, this study aims to analyze previous and current research on the shear strengthening of RC deep beams using NSM-CFRP bars. The research findings were gathered from four prominent databases: ASCE, EBSCO, SCOPUS, and Science Direct. A thorough literature review was conducted, focusing specifically on NSM-CFRP for shear strengthening. A total of 56 articles were categorized into three main groups. Group 1 consisted of studies examining the use of NSM for shear strengthening, while Group 2 focused on articles related to the structural behavior of RC members in shear. Group 3 included articles discussing the theoretical aspects of NSM-FRP in enhancing shear strength, aiming to develop a new method for calculating shear effects provided by NSM-FRP. In conclusion, this study highlights three fundamental aspects of this field: (1) the rationale behind utilizing NSM-FRP bars for shear reinforcement and their practical applications, (2) existing challenges and barriers to widespread adoption, and (3) recommendations for enhancing the acceptance and utilization of NSM-FRP bars.

Keywords: Concrete Fiber-reinforced Polymer, Deep Beam, Near-surface Mounted, Shear Strengthening.

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1 Introduction

The durability of RC structures diminishes over time as the structure ages. The resistance of RC concrete members also decreases due to steel corrosion caused by environmental factors.

Therefore, reinforcing concrete members is crucial as it is more time and cost-effective to maintain them rather than rebuild [1]. Various techniques are being utilized to strengthen RC beams, with the use of FRP gaining popularity due to its appealing properties like excellent corrosion resistance, high strength-to-weight ratio, ease of construction, reinforcement of RC structures, and reduced labor requirements compared to traditional methods.

The FRP technique has been effectively utilized since the 1990s, particularly in RC columns and beams to enhance both shear and flexural strength. In the case of strengthening RC beams for shear, various techniques can be employed, such as externally bonding FRP on both sides or completely wrapping the bottom of beams with glass/carbon fiber sheets in a U shape, secured with epoxy adhesive between the concrete surface and the FRP sheets, as illustrated in Figure 1. Alternatively, the second method involves embedding the FRP bars through the concrete member, as depicted in Figure 2, achieved by drilling holes and embedding the FRP bars using epoxy adhesive throughout the depth of RC beams to enhance shear or flexural strength [2]. The FRP technique also enhances resistance to splitting and improves the effectiveness of bond material or the FRP bar against environmental factors.

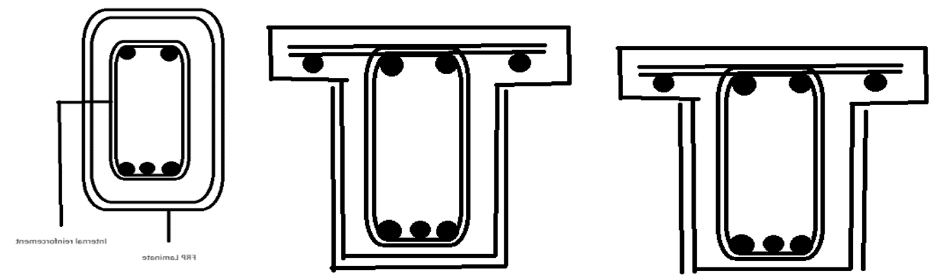

Fig. 1. Wrapping schemes for Externally bonded FRP

Due to the aforementioned benefit, the utilization of CFPR-NSM has led to the recent advancement of a new technique aimed at enhancing the strength of RC members or repairing existing ones. The different groove patterns are illustrated in Figure 3.

Fig. 2. Embedded through section technique

The rise of Fiber-Reinforced Polymer (FRP) materials has been recognized as a substitute material for reinforcing bars in concrete structures. FRP is typically categorized as a composite material and serves as a steel reinforcement alternative because of its high strength-to-weight ratio, durability against corrosion in harsh environments, and other benefits. One notable advantage is the high strength-to-weight ratio of FRP fibers, but the characteristics of the FRP composite are primarily determined by the type of fiber selected [3,4,5]. Flexible Reinforced Polymer (FRP) materials can be affixed to the outside of concrete structures using high-strength adhesives, providing additional reinforcement to complement the internal reinforcement. When cohesive shear failure of the epoxy controls the bond, the shear strength becomes extremely crucial. Two-component epoxy is the best groove filler in terms of performance. The long-term structural behavior of prestressed near surface mounted carbon fiber reinforced polymer (FRP) is influenced by the material properties, which are highly dependent on time and temperature.

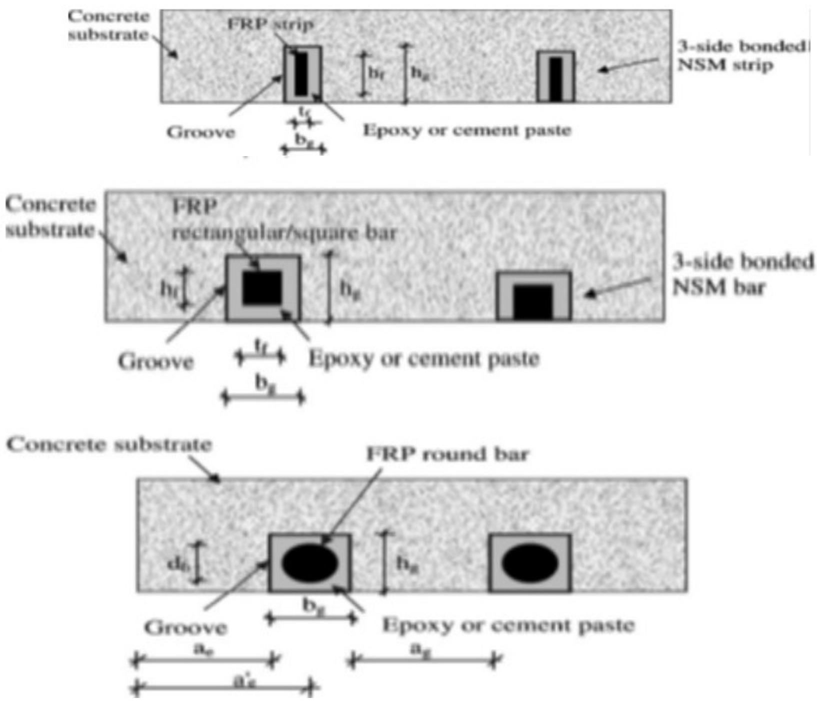

Fig. 3. Various patterns of NSM Techniques.

The FRP composites are made up of 30% to 70% fibers in terms of total volume. The fibers, which account for 50% of the weight ratio, are capable of bearing the load and providing strength, thermal stability, stiffness, and various other structural properties to the FRP. In addition, FRP composites exhibit a high modulus of elasticity, high ultimate strength, minimal strength variation among fibers, consistent strength stability during handling, and uniform diameter and surface dimensions compared to other fiber composites. The matrix plays a crucial role in maintaining the position and alignment of the fibers, safeguarding them from damage during construction and use, ensuring the durability of the composite, and protecting it from environmental influences. Furthermore, the matrix is responsible for distributing the loads evenly across the individual fibers [6,7].

In conclusion, due to its high strength and lightweight properties, FRP composite materials are widely used in the aircraft, sports equipment, and spaceship industries, making it an increasingly popular choice in the construction industry. Additionally, various types of fibers such as carbon (CFRP), glass (GFRP), aramid (AFRP), or basalt (BFRP) fibers are commonly used in civil engineering structures.

2 Experimental method:

The most recent and essential research papers on NSM-CFRP have been thoroughly examined from respected sources such as Journals, Technical Reports, Web Blogs, and others. Additionally, emphasis has been placed on underscoring the significance of the research in question. Moreover, the research gap has been identified by analyzing the literature to enhance the research field. As part of the research process, various activities were carried out, including reviewing the literature to identify challenges and issues in the NSM-CFRP research domain.

The literature review for this research project was conducted using a systematic review method analysis. Four databases (ASCE, EBSCO, SCOPUS, and SCIENCE DIRECT Databases) from 2008 to 2017 were utilized. Additionally, relevant articles from Google Scholar were considered to support the concepts of the review work. Advanced search options in the search engines were employed to exclude book chapters, short communication, correspondences, and letters, ensuring access to the most up-to-date scientific works related to the emergent trend of the NSM technique and its application in shear strengthening of structural members. Each database was searched using a combination of keywords, including "Deep beam" AND CFRP, "Deep beam" AND NSM, "Deep beam" AND "shear strengthening," and "shear strengthening" AND NSM.

Begin by establishing a target to categorize research on NSM-CFRP and its applications in shear strengthening into three main categories. Following the elimination of duplicate articles through scanning, the remaining articles underwent two rounds of filtering based on title and abstract, as well as full-text reading [9-12]. Exclusion criteria encompassed articles that were not in English, focused on the flexural strength of structural members, or involved NSM with other types of FRP bars for strengthening. Despite limited resources on shear strengthening of RC members using NSM-CFRP, the final selection of articles was meticulously classified using the taxonomy. This classification system delineated classes and subclasses within the categories of review, structural behavior, and theoretical studies. Through a comprehensive analysis of studies from various databases, readers are provided with an in-depth understanding of the field.

2.1 Results

The systematic literature review conducted revealed a total of 561 articles. Specifically, 119 articles were sourced from ASCE, 89 articles from EBSCO, 148 articles from Scopus, and 205 articles from Science Direct. Upon initial examination, duplicate articles were eliminated, resulting in 436 articles remaining. Subsequently, a second round of screening was carried out to exclude articles that were not relevant based on their title and abstract. Ultimately, a total of 56 published papers were obtained after a thorough keyword scan related to shear strengthening for structural elements using NSM with CFRP. These 56 papers were found to be the most pertinent to the research topic of the review, encompassing experimental studies, numerical studies, and the bond behavior of CFRP bars or laminates within concrete, particularly in the context of strengthening concrete members through the CFRP NSM technique.

The review work on deep beam strength with NSM-CFRP categorizes the results into five groups: experimental, numerical, theoretical, bond, and review studies. A total of 26 published articles were selected from Scopus, with 18 focusing on experimental studies, 3 on bond studies, 3 on theoretical studies, 2 on numerical studies, and 1 on review papers. From the Science Direct database, 15 articles were chosen, including 5 on experimental studies and FRP bond studies, 2 on numerical studies, 2 on theoretical studies, and 1 on review study of NSM applications. ASCE database contributed 8 published articles, with 3 on experimental work, 3 on bond studies, and 2 on theoretical studies. Lastly, the EBSCO database had 6 selected articles, with 5 on experimental work and 1 on FRP bond studies.

2.2 Review

The research conducted by 6 and 7 on the Near-Surface-Mounted (NSM-FRP) technique determined that it is currently the most advanced, promising, and effective method for enhancing both shear and flexural strength. It was also established that, based on prior experimental investigations, as well as analytical and numerical studies, NSM is a highly efficient and reliable technique for bolstering the strength of concrete components and Unreinforced Masonry Wall (USM) against shear forces.

3 Experimental Studies

The experimental studies conducted in this research work focus on structural behavior. Within this category, the experimental work aims to assess the structural behavior. The research conducted by 8 examined the shear strengthening behavior of four rectangular RC beams and concluded that NSM-CFRP improved shear strength by 24.4%, 17%, and 19.5% compared to the control RC beam. Additionally, it was observed that shear strength increased by approximately 17% - 25% with NSM, and the average shear strength gain was over 20%9. Similarly, a study conducted by 10 investigated the behavior of nine RC beams and found that shear capacity increased by approximately 16% when externally bonded laminates were used, and by a range of 22% to 44% for beams strengthened with NSM-CFRP bars. Furthermore, the effectiveness of using NSM-CFRP for shear strengthening was examined by 11, who found that the ultimate shear strength increased by a maximum of 253% compared to the control beam [15]. Both techniques were utilized in their research, and it was concluded that beam failure occurred at shear cracks, with the average strain obtained through NSM being higher than EBR. Continuing this discussion, a study conducted by 12 investigated nine cantilever RC beams and demonstrated that NSM provided an increase in shear strength ranging from 57% to 112%, along with maximum strain values of 21% and 88%.

The flexural strength and load-carrying capacity of the RCC beam are directly influenced by the ratio of CFRP. Research findings indicated that NSM CFRP strips with a reinforcement ratio of 0.4% for longitudinal steel exhibit a 50% increase compared to other selected ratios. Additionally, the NSM-CFRP technique is effective even with lower concrete strength (18.6 MPa), resulting in improved load-carrying capacity. This effectiveness is maintained even after the occurrence of shear cracks. However, inclined CFRP laminates are found to be more effective in enhancing shear capacity. The study conducted in 2020 demonstrated that the NSM technique is more effective than the Externally-Bonded technique. The use of NSM-CFRP rods reduces the maximum slip of the tensile steel bars and does not significantly affect the load capacity on NSM CFRP rods in corroded beams with an l/d ratio of less than 221. The NSM technique was applied to seven RC beams, resulting in a 43.6% improvement in shear strength and a 34.6% improvement with pre-grooved cuts. Additionally, the results indicated that epoxy resin performs better than mortar. Moreover, the NSM technique can enhance natural frequencies compared to before the insertion of CFRP. The shear capacity and failure displacement of twelve pre-stressed RC beams were improved by 52.0% and 34.4% respectively. However, for beams reinforced with shear stirrups at 90° and 45° angles, the shear improvement was approximately 50% and 54% respectively. Furthermore, a study on twelve T-cross section RC beams revealed that the use of CFRP laminates at different percentages and inclinations (90°, 60°, and 45°) increased shear capacity by 33% for 60° inclination. The load capacity for 45° inclination was 28.2% lower than that of 60° inclination, while the vertical 90° inclination provided a 26.5% increase in load capacity. Another study on four T-beams using the NSM-CFRP technique showed a 15 to 18% improvement in shear capacity compared to the control beam. Similarly, a study on fifteen T-cross section beams concluded that NSM is more effective than EBR in terms of load-carrying capacity, with the 45° inclination being the most effective.

NSM application decreases diagonal cracking caused by various load levels, while NSM-CFRP enhances the shear cracking resistance of T-beams by 23% to 85%. Additionally, NSM leads to enhancements in both maximum load and load-carrying capacity post-shear cracking. However, a more significant improvement in shear capacity is noted in inclined laminates.

Moreover, the utilization of NSM leads to an average enhancement of 60 MPa in the compressive strength of concrete. It also increases the maximum load capacity by approximately 40% to 53%, while the maximum strain improvement ranges from 74% to 94%30. This finding is consistent with the research conducted by 31, which demonstrates the effectiveness of the NSM technique in enhancing the shear strength of RC beams. Various configurations of NSM-CFRP have been employed to enhance the load capacity after shear crack and the maximum load [17,18]. However, the shear contributions of NSM-CFRP are constrained by the compressive strength of concrete in the forty-nine T-beams studied. NSM CFRP strips have been shown to increase the shear strength of retrofitted wall panels by 1.3-2.6 times for walls and 1.3-3.7 times for panels32. Additionally, the study conducted by 33 confirms that NSM significantly improves the overall behavior of RC beams, leading to an average increment of up to 31% in load failure and a reduction in maximum deflection compared to the control beams.

NSM technique has proven to be more effective than EB due to the debonding factor. Research has shown that the punching shear strength increased by 29% when compared to an un-strengthened flat slab, and by 14% for NSM strengthening. Furthermore, there were no instances of debonding failure with NSM. Although there was no observed improvement in shear stress, maximum strains ranging from 0.15% to 0.20% were recorded for CFRP34. A study involving 35 samples indicated that the maximum load increased by 66%-81%, while the maximum tensile strain in laminates rose from 12.2% to 16.3%. The ultimate tensile strain of laminates saw a 69% improvement, with inclined laminates offering greater ductility. The use of NSM-CFRP for shear strengthening of RC deep beams by 36 resulted in an increase in shear capacity from 17.3% to 25.5%, and a reduction in deflection from 6.1% to 16.3% compared to the control beam. Finally, research conducted by 37 demonstrated that shear strength increased by 21%-83%, and tensile strain ranged from 54%-81% for five T-cross section beams.

3.1 Result Distribution

The data presented in Figure 4 illustrates the breakdown of the total number of articles analyzed in this study. These articles have been categorized into ten groups based on the year of publication ranging from 2010 to 2022. In 2010, only one article with experimental research was published, while 10 articles were released between 2011 and 2013. The year 2014 saw the highest number of publications (11), with a significant portion of them being experimental studies. Additionally, a total of 13 articles were published in both 2015 and 2016. Conversely, only one article from 2018 was deemed relevant to the scope of this research. Finally, a total of 19 articles were published between 2021 and 2022.All the papers where completely studied and categorized in a proper manner with a graphical form.

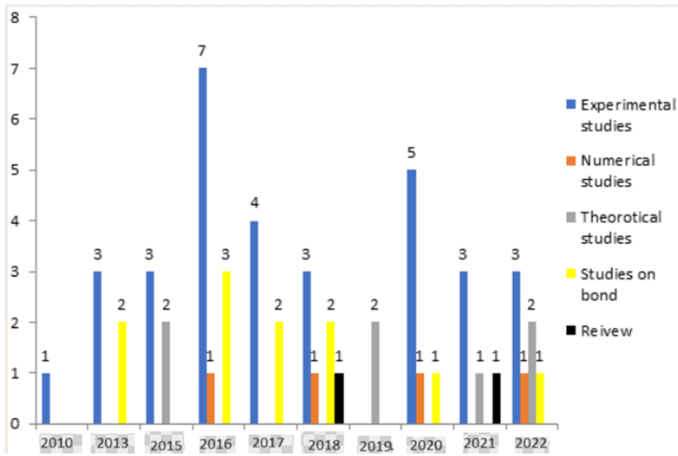

Fig. 4. Result distribution by data analysis

3.2 Distribution by Year of Publications

The distribution of publications based on the author's country, which are related to NSM-CFRP for improving shear strength of structural members, is depicted in Figure 5. A total of 20 countries' authors' publications were reviewed in this research. The literature review included a selection of 58 articles. The distribution of these articles reveals that Portugal is the most interested country, with 13 articles covering various cases. Italy follows closely with 10 articles, while the United States contributed 8 case studies. France and Canada each had 3 and 2 case studies respectively, while Spain, India, Slovakia, and Kuwait had 2 case studies each. The remaining countries were represented by a single article case study, including Australia, Brazil, Switzerland, Egypt, Iraq, New Zealand, Belgium, Turkey, Iran, South Korea, and Malaysia.

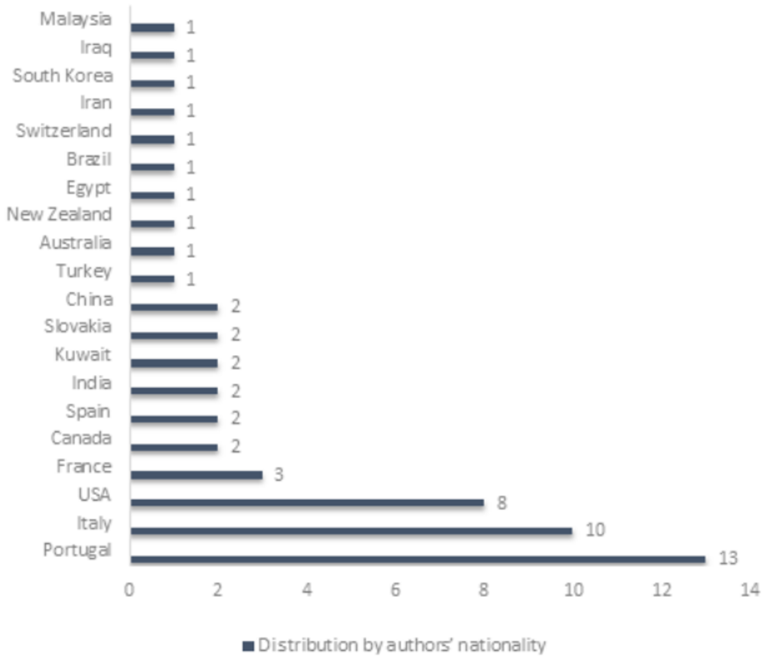

Fig. 5. Result distribution by data analysis.

3.3 Discussion

Based on the final selected articles, the utilization of NSM-CFRP proves to be an extremely efficient method for enhancing the shear strength of structural components. The analysis revealed that there is still limited research on deep structural elements, with most studies focusing on experimental and numerical investigations conducted on simply supported beams and T cross beams [17] . However, there were a few exceptions, such as the study of 32 which examined masonry walls and the case study of 34 which focused on slabs. Nevertheless, the majority of the remaining studies concentrated on bond. These research articles greatly contribute to filling the research gap in the subject area explored by the authors. All the reviewed articles demonstrate that the presence of shear cracks has no impact on the shear strength when utilizing the NSM-CFRP technique, in comparison to uncracked elements. When considering different orientations of CFRP, whether in the form of bars or laminates, a 45-degree inclination provides the highest shear strength compared to other angles[20-26]. Lastly, when comparing experimental and numerical studies, it is evident that numerical studies exhibit a high level of accuracy in terms of crack patterns and load-deflection curves. Based on the literature review, it is concluded that the NSM-CFRP technique is the most effective method when compared to externally bonded EB and embedded through-section techniques.

4 Conclusion

This review study aims to contribute valuable insights by conducting a survey and categorizing the use of the NSM-CFRP technique in shear strengthening. A comprehensive systematic review was conducted, analyzing the latest and critical research articles. These articles were roughly classified into four categories: reviews on the NSM technique and its applications, behavior of structural elements under shear strengthening, studies on the bond between FRP and concrete members, and theoretical studies on the shear contribution of NSM-FRP with design procedures. Through the analysis of these collected articles, the effectiveness and benefits of the NSM-FRP technique were identified, highlighting its emerging field of research and providing recommendations for its use in shear strengthening. The results, supported by statistical explanations, shed light on the information presented in the collected articles and identify existing gaps in the use of NSM-CFRP technique for shear strengthening in RC members.

The authors of the selected articles described the problems, provided proper recommendations and advice, and helped identify authentic research gaps. Based on these findings, it is concluded and recommended to expand the implementation of NSM-FRP for RC deep beams, composite structures, and masonry walls. This conclusion encourages further research on the shear strengthening of structural elements using the NSM-FRP technique, incorporating different devices or embedded sensors in real-life scenarios. In conclusion, it is recommended to pursue interdisciplinary approaches with other technological and scientific fields to further advance research in this area.

References

1. W.S. Barham, Y.T. Obaidat, A. Al-Maabreh, Civil Engineering 31 (12) (2019).
2. Mohamed Ibrahima, Tadesse Wakjiraa, Usama Ebeada, 20 February by Elsevier (2020).
3. M. Yaqub, C.G. Bailey, Construction Building Materials (25) 359–370 (2017).
4. Jamal A. Abdallaa, Raed Abokwieka, Rami A. Hawileha, ICSI 2021 4th International Conference on Structural Integrity (2022).
5. Y.T. Obaidat, G. Abu-Farsakh, A. Ashteyat, Construction Building Materials 198 (1)

(2019) 313–322, Elsevier (2019).
6. Younes Jahani, Marta Baena, Cristina Barris, Torres, Sena-Cruz published by Elsevier (2022).
7. H.Al-Nimry, A. Soman, Engineering Structural 164, 92–108 (2018).
8. D.M. Nguyen, T.K. Chan, H.K. Cheong, J. Composite Construction 5 (2002).
9. H. Toutanji, P. Balaguru, J. Mater. Civ. Eng. 10 (2002).
10. L. Lam, J. Teng, Construction Building Materials 17 (6–7) 471–489 (2003).
11. M. Yaqub, C.G. Bailey, Composite Structure 93, 1103–1117 (2011).
12. O. Ali, Construction Building Materials 151 (2017) 370–382.
13. Y.T. Obaidat, R. Haddad, M. Abdulwahab, Construction Building Mater (2018).
14. T. Pham, M. Hadi, Construction Building Materials 69, 83–90 (2014).
15. ACI Committee318. Building Code Requirements for Structural Concrete Commentary (ACI 318R–014), American Concrete Institute, (2014).
16. H.K. Chinthapalli, M. Chellapandian, ASTM Book of Standards, (2020).
17. Hui Peng, Hao Wang, Junmin Chen, and Kebo Zhang, IEEE, DOI 10.1109/ICDMA.2013.138 (2013).
18. S. Rocca, N. Galati, A. Nanni, Construction Building Materials 23 (4) 1508–1520 (2009).
19. M. Hadi, Constr. Build. Mater. 23 (2) 1102–1108 (2009).
20. M. Demers, K. Neale, Can. J Civil Engineering 26 (2) 226–241 (2000).
21. Arunkumar, K., Muthukannan, M., Kumar, A. S., Ganesh, A. C., & Devi, R. K. (2022). *Applied Science and Engineering Progress*, *15*(1), 1–13. https://doi.org/10.14416/j.asep.2021.06.005
22. Arunkumar, K., Muthukannan, M., Suresh kumar, A., & Chithambar Ganesh, A. (2021). *Environmental Research*, *194*(December 2020), 110661. https://doi.org/10.1016/j.envres.2020.110661
23. Arunvivek, G. K., & Rameshkumar, D. (2022). *Journal of The Institution of Engineers (India): Series A*, *103*(2), 445–451. https://doi.org/10.1007/s40030-021-00604-2
24. Prithiviraj, C., Swaminathan, P., Kumar, D. R., Murali, G., & Vatin, N. I. (2022). *Buildings*, *12*(7). https://doi.org/10.3390/buildings12070965
25. Sankar, B., & Ramadoss, P. (2022a). *International Journal of Engineering, Transactions B: Applications*, *35*(8), 1629–1640. https://doi.org/10.5829/IJE.2022.35.08B.19
26. Sankar, B., & Ramadoss, P. (2022b). https://doi.org/10.1007/978-981-16-4321-7_45