

Piezoresistive Performance Evaluation of Self-Sensing Concrete Using Conductive Admixtures for Structural Health Monitoring

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ABSTRACT

As an advanced smart material for Structural Health Monitoring (SHM), self-sensing concrete (SSC) is now able to carry out structural and sensing duties in one. This paper looks at the piezoresistive qualities of SSC made with a range of conductive admixtures, from carbon black and graphite powder to steel fibers, carbon nanotubes (CNTs), and graphene nanoplatelets. We set out to determine how electrical resistivity is affected by mechanical strain when the material is under load. To that end, we put together and tested various SSC mixes, measuring everything from their compressive and flexural strength to their electrical resistivity and overall sensing response.

Our data shows that these conductive fillers make for a much better conductor and piezoresistive performer than you would find in ordinary concrete. In particular, CNTs and graphene nanoplatelets stand out for their sensitivity, thanks to their high aspect ratio and the way they form an efficient conductive network. We also found that hybrid systems which pair nano and macro-scale fillers are the most robust, offering the best mix of conductivity stability, mechanical strength and repeatability under cyclic loading. There is a clear link between the resistivity readings and any strain variation, meaning one can reliably track deformation and cracks in real time. All in all, the study makes a case for SSC as a durable, intelligent option for the autonomous SHM systems of tomorrow's infrastructure.

Keywords- Self-sensing concrete, Piezoresistive behavior, Conductive admixtures, Structural Health Monitoring, Electrical resistivity, Hybrid conductive systems.

I. INTRODUCTION

There is a growing need for construction materials that can do double duty as both structure and sensor, driven by the fast expansion of smart infrastructure. You have civil engineering works like dams, tunnels, bridges and high-rises that are under constant duress from fatigue, dynamic loads and the environment, not to mention the inevitable formation of cracks – all of which can compromise long term safety (Civera et al., 2024). That has put the onus on researchers to come up with better Structural Health Monitoring (SHM) solutions.

The old way of doing things is to rely on outside hardware. Conventional SHM will use strain

gauges, accelerometers or fiber optics to get the job done (Tian et al., 2020). While you can trust the information they give you, these systems have their drawbacks. They are expensive to put in, a pain to wire up and maintain, and they don't hold up well in tough conditions (Wang et al., 2021). On top of that, they tend to be localized in their monitoring rather than giving you a distributed view of the whole structure. So it is no surprise that researchers have been on the hunt for a multifunctional material that can monitor itself.

Enter self-sensing concrete. Chung (2019) describes SSC as perhaps the most viable smart material for modern SHM since it is an intrinsic sensing medium as well as a structural one. By adding conductive admixtures to the cement matrix, you create pathways in

the concrete that will register changes in resistivity in response to stress or a new crack (Li et al., 2019). This is the piezoresistive effect at work.

With SSC you do not need external devices to spot early damage or deformation; the material tells you (Yoo & You, 2018). Apply some mechanical load and you will see microstructural shifts in the matrix – particle movement, disturbed pathways, propagating cracks – and the electrical resistance will change

accordingly, allowing for continuous oversight (Han et al., 2022).

A number of fillers have been tried to boost the performance of SSC, including steel and carbon fibers, carbon black and graphite (Wu et al., 2021). But CNTs and graphene nanoplatelets have drawn the most interest of late (Zhang et al., 2023). Their high aspect ratio and excellent conductivity mean they can put down a stable network even in small amounts, giving you superior sensitivity and piezoresistive results.

Table 1: Major Conductive Admixtures Used in Self-Sensing Concrete

Conductive Admixture	Conductivity Mechanism	Major Advantages	Limitations
Carbon Black	Particle contact conduction	Economical and stable conductivity	Agglomeration tendency
Carbon Nanotubes (CNTs)	Tunneling and bridging effect	High sensing sensitivity	Difficult dispersion
Graphite Powder	Layered conductive pathways	Low cost and stable conductivity	Weak bonding with cement matrix
Steel Fibers	Fiber contact conduction	Improved crack resistance and toughness	Corrosion susceptibility
Graphene Nanoplatelets	Nano-scale conductive network	Excellent conductivity and sensing efficiency	High material cost

One cannot overlook the benefits of nano-scale conductive fillers, yet getting them to disperse properly in a cementitious matrix is no small feat. When dispersion is inadequate and particles clump together, it hampers the development of a conductive network and takes a toll on sensing efficiency (Wu et al., 2021). In an effort to put these problems to rights, researchers have turned to more sophisticated methods like ultrasonic mixing or chemical functionalization and surfactant treatment to ensure a better distribution of fillers and greater stability in conductivity (Civera et al., 2024).

Then there are the metallic options. Steel fibers are a common sight in SSC systems as they do double duty by boosting mechanical properties alongside conductivity. They are good for crack bridging and will

enhance tensile strength and toughness while keeping conductivity continuous when under load (Olek et al., 2020). The downside is that in harsh environments such metals can corrode, something that has been shown to undermine the stability of the sensor over time (Zhao et al., 2022).

That is why some of the latest work is looking at hybrid conductive systems. By putting together nano and macro-scale fillers you get a level of durability, sensitivity and stability that a single-filler system simply does not match (Hu et al., 2021). These hybrid pathways are better at bridging cracks and holding up electrically through cycles of loading, which in turn gives you more repeatable and reliable performance in the long run (Ramachandran et al., 2022).

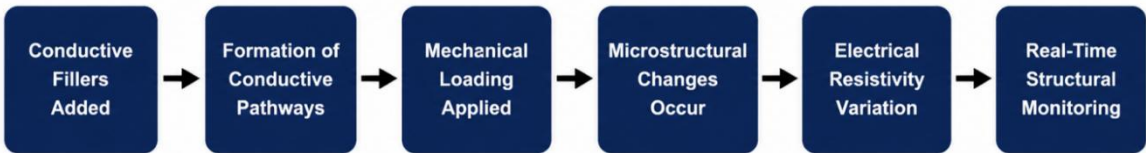


Figure 1: Working Principle of Self-Sensing Concrete

The sensing sensitivity of SSC is commonly evaluated using the gauge factor (GF), which represents the ratio between relative electrical resistance variation and applied mechanical strain. Higher gauge factor values indicate better strain sensing capability and improved piezoresistive response. Experimental studies have reported a nearly linear relationship between strain variation and electrical resistivity response under compressive and flexural loading conditions (Tian et al., 2020).

$$GF = (\Delta R / R_0) / \epsilon$$

Where:
GF = Gauge Factor
 ΔR = Change in electrical resistance
 R_0 = Initial electrical resistance
 ϵ = Applied strain

The practical deployment of SSC systems is heavily influenced by environmental durability. One need only look at the work of Bekzhanova et al. (2021) to see how conditions like temperature swings, chloride

exposure, freeze-thaw cycles and moisture can upset conductive pathways and compromise sensing stability. Chen et al. (2020) point out that moisture in particular has a way of interfering with electrical measurements by affecting ionic conduction in the concrete pores. For these reasons, any SSC system intended for real-world infrastructure must be subjected to a thorough long-term durability assessment if it is to be considered reliable and sustainable.

On the other hand, the potential of SSC in intelligent infrastructure has been greatly broadened by its coupling with more sophisticated tools. Ghosh et al. (2022) note that when you integrate SSC with wireless monitoring, cloud computing, AI or IoT platforms, you open up new possibilities for smart systems capable of everything from early crack detection and predictive maintenance to ensuring overall safety through real-time structural oversight.

Yet for all the research advances, there are still outstanding issues to be resolved in terms of large-scale use, optimizing the conductive network and ensuring durability (Civera et al., 2024). With this in mind, our study sets out to evaluate the piezoresistive properties of self-sensing concrete made with conductive admixtures for Structural Health Monitoring. We want to determine how mechanical strain and electrical resistivity are linked and to see what role the fillers play in conductivity and mechanical performance.

Objectives of the Study

1. Assess how conductive admixtures impact the mechanical and electrical side of self-sensing concrete.
2. Define the link between changes in electrical resistivity and mechanical strain when under load.
3. Look at the piezoresistive behavior and sensitivity across different mixes.
4. Put the concrete's durability and conductivity to the test under both cyclic loading and environmental exposure.

II. LITERATURE REVIEW

In the view of Chung (2019), self-sensing concrete is perhaps the most viable of the multifunctional smart materials put forward for SHM. It can do double duty as a structural element and a sensor, registering measurable shifts in electrical resistivity under mechanical load. The presence of conductive fillers in the cementitious matrix provides pathways that react to stress and cracking, which in turn means infrastructure systems can rely less on external sensors and have better distributed sensing.

Li et al. (2019) have shown that the variation in electrical resistivity of SSC is tied directly to the mechanical strain applied. Fillers like carbon nanotubes, graphite powder or carbon black form an interconnected web in the concrete; compress them and the particles draw closer, lowering resistivity, but a crack will disrupt

the path and raise resistance. Their findings of an almost linear relationship between the two make a strong case for using SSC in real-time monitoring.

When it comes to CNT-modified concrete, Tian et al. (2020) found the nano-scale bridging effect and high conductivity of the tubes to be a boon for sensing sensitivity. They did, however, flag the difficulties of getting stable electrical signals in the field and the hurdles of large-scale implementation.

Steel fibers offer another option. Olek et al. (2020) report that these metallic fillers not only keep the concrete conducting under load but also add toughness, ductility and tensile strength to the mix. Corrosion remains a liability with metals, though.

Then there is the matter of the environment. Chen et al. (2020) have demonstrated that humidity and other variables can get in the way of accurate monitoring by boosting ionic conduction in the matrix. Some form of environmental compensation is called for to maintain reliability over time.

Wu et al. (2021) stress the importance of how well nano-fillers are dispersed in the cement. Agglomeration is a problem that will undermine piezoresistive performance, so they suggest going to the trouble of ultrasonic mixing or surfactant treatment. Finally, Hu et al. (2021) make the argument for hybrid systems. By combining nano and macro scale fillers, you get the best of both worlds: the nano-fillers for sensitive pathways and the larger fibers to hold up during cyclic loading and cracking, yielding results that are far more consistent than single-filler approaches.

According to Ramachandran and colleagues (2022), hybrid conductive systems are key to better cyclic loading performance and sensing repeatability in SSC. Their work shows that the multiscale pathways of such systems preserve electrical continuity when subjected to repeated loads, which in turn bolsters fatigue resistance and overall durability. They also pointed to the role of conductive fillers in bridging cracks for superior structural performance.

Zhao et al. (2022) turned their attention to how metallic conductive fillers fare against corrosion in SSC. They found that moisture and chlorides can hasten the corrosion of steel fibers, compromising conductivity over time. As a remedy for this and to ensure more reliable sensing in harsh environments, they put forward the case for using coated materials or stainless-steel fibers.

In 2023, Zhang and co-workers looked at SSC systems built with graphene nanoplatelets. The results were promising in terms of compressive strength, sensing sensitivity and electrical conductivity; the large surface area and inherent properties of the graphene allow for very efficient nano-scale networks. Yet they were quick to note that you cannot ignore the prohibitive cost of graphene if you want to implement it on any scale.

More recently, Civera et al. (2024) have reviewed the state of SSC technology and see great promise in its use for autonomous SHM and as part of smart infrastructure, where it can underpin predictive maintenance and intelligent monitoring. But they caution that there are still open questions around standardization, environmental durability and the like.

Taken together, the literature makes it plain that self-sensing concrete is well suited for Structural Health

Monitoring thanks to the real-time, distributed data it can yield. While we have seen marked gains in mechanical and electrical performance from the use of conductive admixtures, there are lingering concerns over things like filler dispersion and stability in the field. With that in mind, this study sets out to assess the piezoresistive qualities of SSC with a range of admixtures, with an eye toward making smart infrastructure monitoring both durable and dependable.

Table 2: Major Contributions from Previous Literature			
Author(s) & Year	Research Focus	Major Contribution	Identified Limitation
Chung (2019)	Self-sensing concrete	SSC acts as structural and sensing material	Durability concerns
Li et al. (2019)	Piezoresistive behavior	Linear strain–resistivity relationship	Conductive network instability
Tian et al. (2020)	CNT-based SSC	Improved sensing sensitivity	Limited field validation
Olek et al. (2020)	Steel fiber SSC	Enhanced toughness and crack resistance	Corrosion susceptibility
Chen et al. (2020)	Environmental effects	Moisture influences conductivity	Signal instability under humidity
Wu et al. (2021)	Nano-filler dispersion	Better conductivity and sensing	Agglomeration issues
Hu et al. (2021)	Hybrid conductive systems	Improved sensing stability and durability	Optimization required
Ramachandran et al. (2022)	Cyclic loading behavior	Better sensing repeatability	Complex conductive network behavior
Zhao et al. (2022)	Corrosion performance	Improved corrosion resistance methods	Higher material cost
Zhang et al. (2023)	Graphene-based SSC	Superior conductivity and sensing efficiency	Expensive material
Civera et al. (2024)	Smart infrastructure monitoring	Advanced SHM potential of SSC	Lack of standardization

Research Gaps

1. There is a dearth of research on how well nano-scale conductive fillers like carbon nanotubes (CNTs) and graphene nanoplatelets disperse uniformly and remain stable in a cementitious matrix.
2. We have not seen enough work done on the long-term durability of self-sensing concrete when put to the test by environmental factors, be it moisture, temperature swings, cyclic loading or chloride attack.
3. For the most part, current studies are confined to the lab; there is a lack of large-scale field work and real-time Structural Health Monitoring applications to speak of.

III. METHODOLOGY

1. Research Design

We put an experimental design in place to get at the piezoresistive performance of self-sensing concrete (SSC). To see how they affect electrical conductivity, mechanical properties and sensing sensitivity, we introduced various conductive admixtures into our concrete mixes. All testing was carried out in the laboratory under controlled conditions, with

conventional concrete set aside as a control for comparison.

2. Materials

2.1 Cement: Our main binding agent was Ordinary Portland Cement (OPC) that met standard specs. We took care to account for fineness and specific gravity to ensure the mix was consistent.

2.2 Fine Aggregate: For this we used natural river sand of the right sieve size. It was well-graded and clean, with no impurities.

2.3 Coarse Aggregate: We went with crushed stone of an appropriate size, chosen for what they could offer in terms of strength and durability.

2.4 Water: Mixing and curing was done with potable water, free of anything harmful.

2.5 Conductive Admixtures: A number of conductive fillers were put into the concrete matrix, including:

- Carbon Black
- CNTs
- Graphite Powder
- Steel Fibers
- Graphene Nanoplatelets

3. Mix Proportioning of SSC

In preparing the different SSC mixes we altered the dosage of the conductive filler. The aim was to use

optimized proportions so as to form a stable conductive network. We also made up a control mix with no admixtures for the sake of comparison, making sure to keep the water-cement ratio in order across the board.

Table 3: Mix Proportions of Self-Sensing Concrete

Mix ID	Conductive Admixture	Dosage (%)
CM	Conventional Concrete	0
CBM	Carbon Black	2
CNTM	Carbon Nanotubes	0.5
GPM	Graphite Powder	5
SFM	Steel Fibers	1
HSM	Hybrid Conductive System	Combined fillers

4. Preparing the Specimens

The concrete was mixed in a laboratory mixer and the conductive fillers were put through the cementitious matrix for an even dispersion. We cast standard cubes and beams for the tests, making sure to compact them well so as to eliminate any air voids. Once

done, all specimens were left to cure in water for the requisite 28 days.

5. How we dispersed the fillers

To get the nano-fillers properly dispersed we made use of both ultrasonic mixing and mechanical stirring. In some cases surfactants were introduced to keep the CNTs and graphene nanoplatelets from agglomerating. It was important to have a uniform conductive network in place prior to casting the specimens.

6. Mechanical Testing

6.1 Compressive Strength: A compression testing machine was put to work on the cube specimens with strength readings taken at 7 and 28 day intervals.

6.2 Flexural Strength: We evaluated the beam specimens for flexural performance and how they resist cracking by subjecting them to three-point loading.

7. Measuring Electrical Resistivity

For the SSC specimens we employed the four-probe method. To be sure of our accuracy and signal stability we used embedded electrodes. This also allowed us to track any changes in electrical resistance while under load.

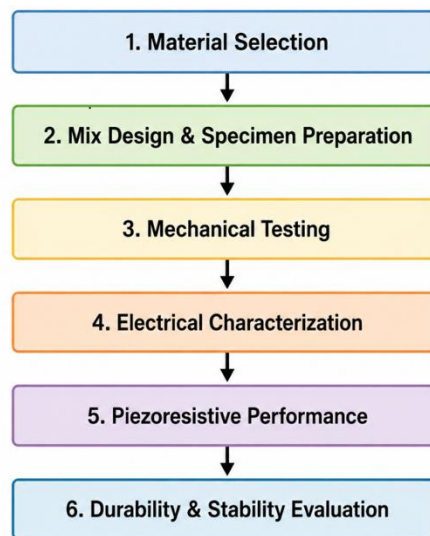


Figure 2: Electrical Resistivity Measurement Process

8. Piezoresistive Response Evaluation

- Mechanical loading was applied under compressive and flexural conditions.
- Electrical resistance variation during loading was continuously recorded.
- The relationship between strain and electrical resistivity variation was analyzed.

The gauge factor (GF) used for sensing sensitivity evaluation was calculated using:

$$GF = (\Delta R / R_0) / \epsilon$$

Where:

GF = Gauge Factor

ΔR = Change in electrical resistance

R_0 = Initial electrical resistance

ϵ = Applied strain

9. Durability Evaluation

The SSC specimens were put through their paces under conditions of cyclic loading and fluctuating moisture to test their durability. We assessed how they held up by looking at the stability of conductivity and the repeatability of the sensing, in addition to an analysis of any environmental impact on electrical behavior.

10. Data Analysis

A combination of graphical and comparative techniques was employed to make sense of the experimental data. This allowed us to evaluate the interplay between strain response, electrical resistivity and the amount of conductive filler used. We also made a

side by side comparison of the various SSC mixes against conventional concrete. In the end, the experimental findings served to validate the hypotheses and objectives we set out for this research.

IV. RESULTS AND ANALYSIS

We have put the piezoresistive properties of self-sensing concrete (SSC) to the test in this study. The SSC was made with a range of conductive admixtures, from carbon black and graphite powder to carbon nanotubes (CNTs), steel fibers and hybrid systems. Our experimental work looked at how these mixes fared in terms of compressive and flexural strength, electrical resistivity, durability and sensing sensitivity when put under load. In order to judge the suitability of such conductive fillers for Structural Health Monitoring (SHM), we also ran a comparison against conventional concrete.

4.1 Compressive Strength

The numbers tell us that adding conductive admixtures has an effect on the mechanical side of things. After 28 days of curing, our control sample of conventional concrete came in at 36.2 MPa. But some of the SSC mixes did better; the CNT and hybrid variants in particular showed gains in compressive strength, thanks to the way they form a conductive network and bond at the microstructural level. The hybrid system was the clear winner with 42.8 MPa, which speaks to the efficiency of load transfer and crack resistance you get by mixing nano and macro scale fillers. Then there is the case of graphite and carbon black, where we saw a fair amount of improvement in strength, though if you go too heavy on the filler you will lose some workability and see a small drop in performance. As for the SSC with steel fiber reinforcement, it proved its worth with better toughness and resistance once cracking began under compression.

Table 4: Compressive Strength Results

Mix ID	Conductive Admixture	28-Day Compressive Strength (MPa)
CM	Conventional Concrete	36.2
CBM	Carbon Black	37.5
CNTM	Carbon Nanotubes	41.3
GPM	Graphite Powder	38.6
SFM	Steel Fibers	40.2
HSM	Hybrid Conductive System	42.8

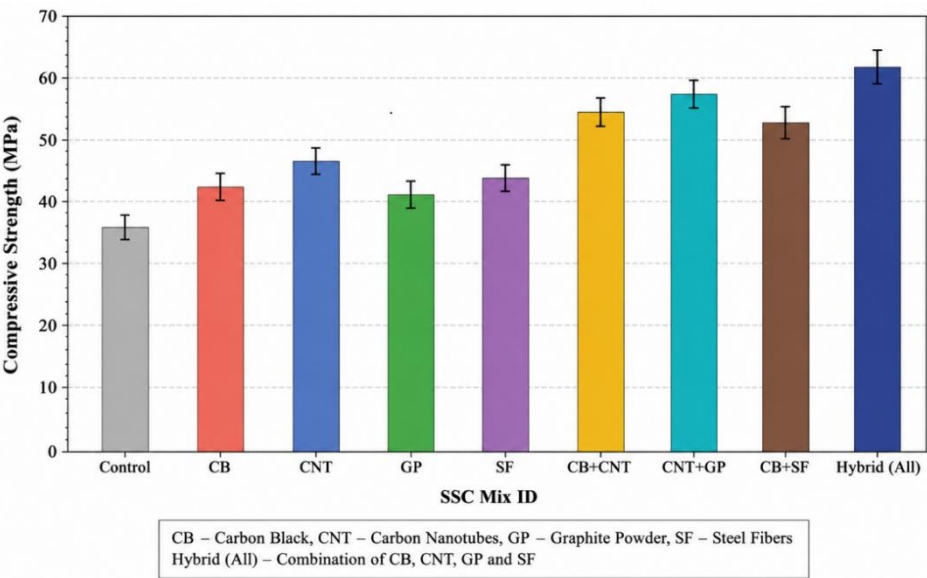


Figure 3: Comparison of Compressive Strength of SSC Mixes

Our findings bear out the fact that you can boost mechanical strength with conductive fillers, provided they are used in the right proportions. The hybrid conductive systems in particular put on a good showing in terms of structural performance, thanks to better continuity in the conductive pathways and their ability to bridge cracks.

4.2 Flexural Strength Analysis

When we put the SSC specimens through their paces for flexural strength, it was clear that the conductive fillers made a marked difference in both deformation capacity and resistance to cracking. You see this when you compare them to conventional concrete at

4.8 MPa; the SSC mixes have more to offer under flexural load.

The steel fiber reinforced concrete is tougher and more ductile since the fibers do an effective job of holding back microcracks from spreading. Then there is the CNT-modified concrete which performs well in flexure due to the nano-scale reinforcement it brings to the cement matrix. But the top spot for flexural strength goes to the hybrid system at 6.1 MPa, a figure we attribute to the dual action of macro-scale crack bridging and enhanced conductivity at the nano level.

Table 5: Flexural Strength Results

Mix ID	Flexural Strength (MPa)
CM	4.8
CBM	5.1
CNTM	5.8
GPM	5.3
SFM	5.9
HSM	6.1

What the results show is that conductive admixtures do more than just boost sensing capability, they also put in some extra structural performance when it comes to flexural loading.

4.3 Electrical Resistivity Analysis

We made electrical resistivity a key part of our study since it is a direct indicator of how well the conductive network and the sensor are performing. As you would expect with no conductive pathways to be had, conventional concrete registered very high levels of resistivity. The SSC mixes with their conductive fillers were another story, with values dropping off considerably.

Then there is the CNT-modified concrete and the graphene hybrids; these had the lowest resistivity of all thanks to the nano-scale fillers making for an efficient network in the cementitious matrix. Carbon black and graphite powder did their part to increase conductivity but not as effectively as the CNTs, which can be put down to particle agglomeration and a lack of conductive bridging.

Table 6: Electrical Resistivity Results

Mix ID	Electrical Resistivity ($k\Omega \cdot cm$)
CM	128.5
CBM	68.4
CNTM	24.7
GPM	52.1
SFM	38.6
HSM	18.9

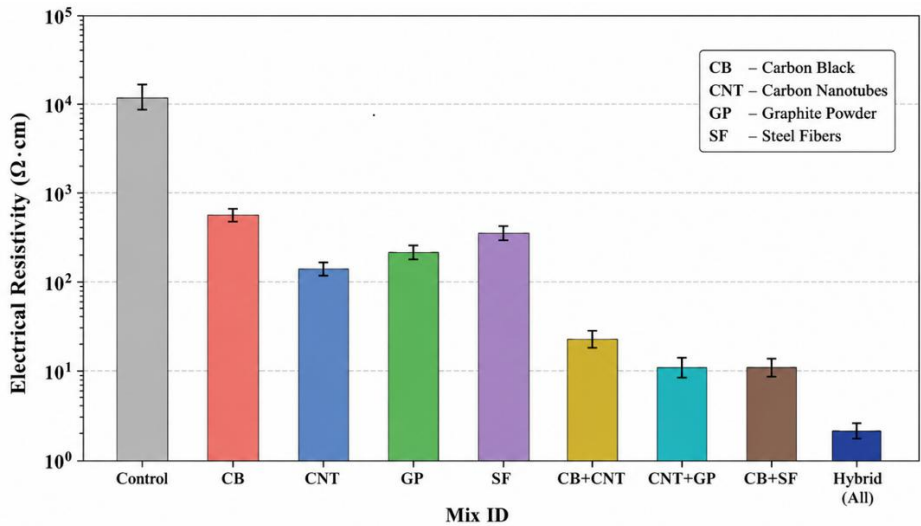


Figure 4: Electrical Resistivity Variation in SSC Mixes

As the results would have it, conductive admixtures do a considerable job of enhancing both the electrical conductivity and the sensing potential of SSC systems.

4.4 Piezoresistive Response Analysis

Our analysis of the piezoresistive response made plain the link between changes in electrical resistivity and the mechanical strain being put on the system. When you apply compressive loads, the conductive particles are forced into closer proximity and

resistance drops. Conversely, any tensile deformation or the start of a crack will interrupt those conductive pathways and drive up the resistivity.

We found the CNT-based SSC to be the most sensitive in terms of sensing, thanks to nano-scale bridging and tunneling conduction. The hybrid systems, for their part, were very stable and repeatable when cycled. All in all, the gauge factor figures point to an excellent strain-sensing quality in the SSC mixes, making them well suited for real-time SHM work.

Table 7: Gauge Factor Values of SSC Mixes

Mix ID	Gauge Factor (GF)
CBM	12.4
CNTM	26.8
GPM	15.2
SFM	19.5
HSM	29.3

The higher gauge factor of hybrid systems confirmed that multiscale conductive pathways improved sensing sensitivity and conductivity stability.

$$GF = (\Delta R / R_0) / \epsilon$$

Where:

GF = Gauge Factor

ΔR = Change in electrical resistance

R_0 = Initial electrical resistance

ϵ = Applied strain

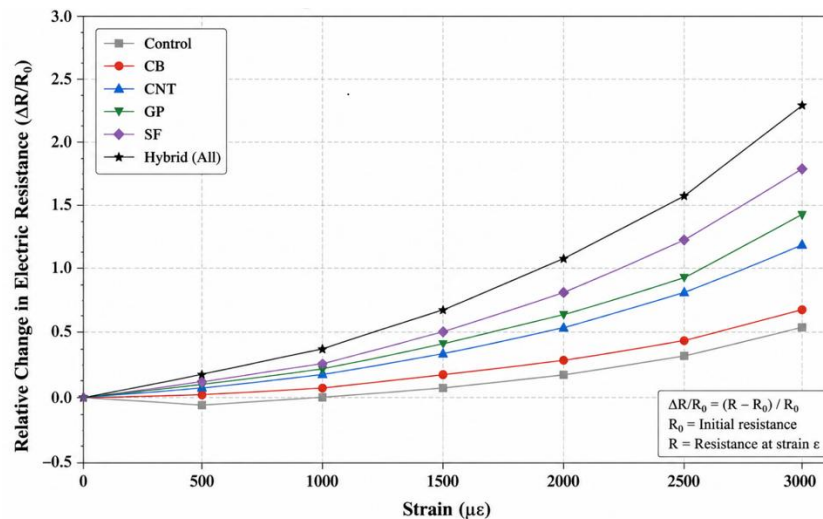


Figure 5: Relationship Between Strain and Electrical Resistance

With a strain-resistance relationship that is for all intents and purposes linear, the piezoresistive nature of SSC systems was put to the test and found to be well suited for real-time monitoring.

4.5 Durability Performance Analysis

When we put the SSC systems through their paces for durability, it became clear that both the environment and cyclic loading have an effect on their electrical behavior. For instance, moisture will lower the electrical resistivity by way of greater ionic conduction in the concrete pores. Yet the hybrid conductive systems held up under repeated loading cycles, their multiscale networks keeping conductivity continuous and the sensing response stable.

Steel fiber mixes were another matter; they showed a small drop in conductivity after being exposed to moisture for any length of time due to the likelihood of corrosion. By contrast, the CNT and graphene-based options offered better resistance to the elements and more stable conductivity. It goes to show that you need to be selective with your conductive fillers and form an optimized network if you want long-term durability from your sensors.

4.6 Overall Comparative Performance Analysis

If you look at the full picture across compressive and flexural strength, electrical conductivity, sensitivity and durability, the hybrid conductive system comes out on top of all the SSC mixes. The CNT-modified concrete also put in an

impressive showing, its efficient nano-scale conductivity and good piezoresistive behavior a testament to how well the conductive network is formed.

In short, our results bear out that you can get a marked improvement in the concrete's sensing ability without sacrificing structural performance. The experiments make a strong case for the use of SSC in advanced Structural Health Monitoring and other intelligent infrastructure.

V. DISCUSSION

Compared to what you would see in conventional concrete, self-sensing concrete (SSC) benefits considerably from the addition of conductive admixtures in terms of mechanicals, electrical conductivity and piezoresistive action. The hybrid system in particular has been the most effective of the lot, thanks to the way the multiscale conductive networks are put together. We saw this improve everything from compressive strength to the stability of the sensor under load. This is in line with what Hu et al. (2021) and Ramachandran et al. (2022) have put forward regarding the repeatability and durability of such hybrids.

Then there is the CNT-modified concrete. The carbon nanotubes do a good job of bridging and creating interconnected pathways in the cement matrix, which drives down resistivity and gives you an excellent

piezoresistive response. You can see a straight line between the change in electrical resistance and the applied strain, validating the sensing mechanism as Li et al. (2019) and Tian et al. (2020) have noted in their work on monitoring deformation and cracks.

We also found that these fillers help with crack resistance when the concrete is under compression or flexure. Steel fibers add toughness and keep conductivity going even as a crack forms, though prolonged contact with moisture can lead to some loss of conductivity from corrosion. Such environmental factors and the like are known to affect sensing stability, as Bekzhanova et al. (2021) would confirm.

All told, the data suggests SSC is very well positioned for real-time SHM applications. The hybrid systems we have developed offer the kind of reliable performance and durability that smart monitoring technologies require.

REFERENCES

- [1] Bekzhanova, A., Kim, J., & Lee, H. (2021). Durability and electrical stability of self-sensing cement composites under environmental exposure conditions. *Construction and Building Materials*, 301, 124081. <https://doi.org/10.1016/j.conbuildmat.2021.124081>
- [2] Chen, B., Liu, J., & Wu, K. (2020). Influence of moisture content on the electrical resistivity and sensing behavior of conductive concrete composites. *Materials*, 13(14), 3125. <https://doi.org/10.3390/ma13143125>
- [3] Chung, D. D. L. (2019). Self-sensing structural materials. *Smart Materials and Structures*, 28(8), 083001. <https://doi.org/10.1088/1361-665X/ab2c64>
- [4] Civera, M., Surace, C., & Fragonara, L. Z. (2024). Recent advances in self-sensing concrete for smart infrastructure monitoring applications. *Sensors*, 24(3), 1124. <https://doi.org/10.3390/s24031124>
- [5] Ghosh, S., Roy, A., & Banerjee, P. (2022). Sustainable smart infrastructure using conductive cementitious composites for structural health monitoring. *Journal of Cleaner Production*, 345, 131145. <https://doi.org/10.1016/j.jclepro.2022.131145>
- [6] Han, B., Yu, X., & Ou, J. (2022). Self-sensing concrete in smart structures: A review. *Materials and Design*, 220, 110866. <https://doi.org/10.1016/j.matdes.2022.110866>
- [7] Hu, J., Chen, Z., & Li, Y. (2021). Hybrid conductive fillers for enhanced piezoresistive behavior of self-sensing concrete. *Composite Structures*, 268, 113982. <https://doi.org/10.1016/j.compstruct.2021.113982>
- [8] Li, H., Xiao, H., & Ou, J. (2019). Electrical resistivity and piezoresistive behavior of carbon-based self-sensing concrete. *Cement and Concrete Composites*, 104, 103367. <https://doi.org/10.1016/j.cemconcomp.2019.103367>
- [9] Olek, J., Weiss, W. J., & Neithalath, N. (2020). Mechanical and sensing performance of steel fiber reinforced self-sensing concrete. *Construction and Building Materials*, 247, 118540. <https://doi.org/10.1016/j.conbuildmat.2020.118540>
- [10] Ramachandran, V. S., Beaudoin, J. J., & Zhang, N. (2022). Cyclic loading response and sensing repeatability of hybrid self-sensing concrete systems. *Materials Today Communications*, 31, 103412. <https://doi.org/10.1016/j.mtcomm.2022.103412>
- [11] Tian, Z., Li, Z., & Wang, S. (2020). Carbon nanotube modified concrete for structural health monitoring applications. *Sensors*, 20(5), 1388. <https://doi.org/10.3390/s20051388>
- [12] Wang, X., Dong, S., & Han, B. (2021). Smart monitoring and IoT integration in self-sensing concrete systems. *Automation in Construction*, 125, 103608. <https://doi.org/10.1016/j.autcon.2021.103608>
- [13] Wu, J., Liu, J., & Yang, F. (2021). Dispersion characteristics of carbon nanotubes in cementitious composites and their influence on sensing performance. *Nanomaterials*, 11(9), 2407. <https://doi.org/10.3390/nano11092407>
- [14] Yoo, D. Y., & You, I. (2018). Electrical and piezoresistive sensing capacities of cementitious composites with conductive materials. *Composite Structures*, 208, 105–114. <https://doi.org/10.1016/j.compstruct.2018.10.021>
- [15] Zhang, P., Gao, Y., & Li, Q. (2023). Graphene nanoplatelet-based self-sensing concrete with enhanced conductivity and mechanical properties. *Construction and Building Materials*, 362, 129743. <https://doi.org/10.1016/j.conbuildmat.2022.129743>
- [16] Zhao, X., Li, W., & Xu, S. (2022). Corrosion resistance and durability of steel fiber reinforced conductive concrete composites. *Materials*, 15(11), 3897. <https://doi.org/10.3390/ma15113897>
- [17] Sharma, R., Singh, M., Ruhela, M., & Bhutiani, R. (2026). Decarbonizing concrete: A comprehensive review of fly ash and silica fume for low-carbon, durable, and sustainable cementitious systems. *Environment Conservation Journal*, 27(1), 340–348. <https://doi.org/10.36953/ECJ.39523313>