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Plasticizers and Superplasticizers in Concrete Technology: Technical Performance, Market Dynamics and Sustainability Pathways in a Developing Construction Economy

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ABSTRACT

Purpose: *This research is a national-level assessment of the usage of plasticizers and superplasticizers in the concrete industry in Pakistan by analysing technical performance perceptions, market structure, sustainability awareness, and policy barriers.*

Design/Methodology/Approach: *A cross-sectional survey research on 381 construction practitioners (contractors, consultants, RMC managers, suppliers, regulators, academics) was conducted using a structured Likert Scale survey instrument as a survey tool. Descriptive statistics, role-wise comparison, cross-tabulation, and Composite techno-economic analysis were made.*

Findings: *Over 80% of the respondents confirmed that there is technical acceptance for admixture, as they said they had recently used admixture. Workability improvement was the most reliable improvement (Mean = 3.66), whilst strength improvement was considered as conditional (Mean = 3.49). Durability benefits were under-recognised (Mean = 3.15) because of poor measuring practices. Cement--admixture compatibility proved as the major technical barrier (Mean = 2.92, highest variability), side by side with inconsistent slump retention (Mean = 3.02). Economically, 87% of respondents saw that prices have been on an upward trend in the last 3 years, and the result of 3.85/5 for assessing the average cost perception shows that admixtures are generally thought to be expensive. The ensuing techno-economic adoption gap is suggestive of how positive technical performance is no guarantee for adoption in the face of price fluctuation and import dependency. While there was >70% awareness as to relevance to sustainability, cost was the overriding decision factor.*

Implications/Originality/Value: *The study reveals that barriers to adoption in Pakistan are better explained by economic and institutional factors than technical factors. Although the performance benefits are realized, concerns of compatibility, price instability, and cost sensitivity limit low routine usage. By incorporating both market and policy-censured perceptions of performance, this research supports one of the very first empirical assessments on plasticizer and superplasticizer use at the national level in a creating conception, supplying the proof-based CU on compatibility requirements and local production respective the trace amounts of super-superplasticizer application lifecycle-centred programming.*

Keywords*: Plasticizers, Superplasticizers, Concrete Technology, Construction Industry in Pakistan, Market Trends, Sustainable Construction.*

1 Introduction

Concrete is currently the most generally utilized construction material in the standards, and the improvement of its performance keeps on being advanced through the use of chemical admixtures: by all means, plasticizers and superplasticizers. (Amran et al., 2022). These high-range water-reducing admixtures have revolutionized the concrete technology by permitting the usage of a lower water-cement ratio, better workability, better compaction, and higher mechanical strength, without jeopardizing the constructability. (Ünal et al., 2025). Internationally, polycarboxylate ether (PCE), sulphonated naphthalene formaldehyde (SNF), and lignosulphonate-based systems are regularly used for ready-mix applications as well as for precast applications, infrastructure, and high-performance concrete applications. (Barbhuiya, 2025). Their role has increased from that of simple workability-enhancing to that of crucial performance-modifying concrete additives that influence durability, permeability, service life, and sustainability of concrete structures. (Saluja et al., 2025).

Despite these well-documented technical benefits, the behaviour and reliability of plasticizers and superplasticizers are very sensitive to the chemistry of the cement, how the dosage is controlled, to the curing practices, and to the quality assurance systems. Research from developed construction markets establishes that achieving standardization and consistent performance is reliant on compatibility testing, standardized specifications, and institutionalized quality control frameworks. (Firoozi et al., 2025). However, in the case of construction developing economies, such enabling systems are weak or inconsistent, which leads to variation of performance in the field. This renders it true that the benefits which have been proven inside the laboratory don't always translate into the accomplishments around the site, particularly in the area where the variations inside the materials and practices which are being performed on site can be highly different inside the managed conditions which are the subject of the research. (Silva et al., 2024).

In Pakistan, the use of plasticizer and superplasticizer has increased with the increase in no. of high rising building, RMC plant and infrastructural projects. Yet their adoption is still spotty, project-specific, and heavily influenced by economics. Market instability, volatility in prices, import dependency, and the poor state of local manufacturing capacities result in economic uncertainty via financial means. (Sangiorgio et al., 2025). Simultaneously, the inconsistent characteristics of cement and the unsatisfactory culture of prequalification and trial mixtures are causing compatibility issues, causing lack of confidence among users. As a result, admixture ingredients often have been valued for immediate workability benefits and estimated with apprehension about long-term durability performance. (Yang et al., 2024).

There is therefore a vital gap in the research. While there is technical literature available in detail describing the chemical mechanisms involved and laboratory performance of plasticizers and superplasticizers, less information is available empirically that describes how the performance of plasticizers and superplasticizers are being perceived by construction professionals in the developing markets, how economics and the supply chain is affecting the adoption of such chemicals and how the benefits relating to sustainability are being perceived at the industry level. Particularly missing are national-scale studies relating technical performance perception to market behavior, cost-sensitivity, and institutional maturity. (Tariq et al., 2025).

The need that is addressed in this study is the mismatch between the proven technical potentials of plasticisers and superplasticisers and their selective and risk-averse adoption in the construction industry of Pakistan. Without an understanding of how the interaction of technical reliability, economic restrictions, and institutional circumstances plays out, attempts to foster high-performance and sustainable concrete are currently fragmented (Dias et al., 2024).

Accordingly, the objectives of this paper are to: assess industry perception of technical parameters of performance (i.e. workability, retention of slump, strength, durability and compatibility); Identify types and areas of application of plasticizers and superplasticizers in current practices; Analyze size of markets, price trends, import dependency and stability of supply chain assess sustainability-related perceptions, e.g. cement reduction and lifecycle benefits; interpret the aggregate impact of these technical and economic factors on adoption behaviour and prospects. (Ye et al., 2025). This study adds to the body of literature and gives one of the first empirical, industry-scale assessments of the use of plasticizers and superplasticizers in Pakistan. Integrating performance perception with market and institutional analysis thus goes beyond this focus of research done only in the lab and provides the opportunity for a systems-level understanding of the admixture adoption in a developing construction economy. The results are in favour of the development of compatibility standards, local manufacturing initiatives, performance-based specifications, and life cycle-oriented procurement frameworks that are required for reliable and sustainable integration of admixture technology.

2 Literature Review

2.1 Plasticizers and Superplasticizers Development in Concrete

The development of plasticizers and superplasticizers is one of the most important development of modern concrete technology (He et al., 2025). Early generations of water-reducing admixtures were based mainly on lignosulphonate based compound that were derived from the by-products of wood processing. These materials provided good to moderate water reduction, good workability, and were limited in their ability to attain very low water/cement ratios. The second generation, such as sulphonated naphthalene formaldehyde (SNF) and sulphonated melamine formaldehyde (SMF) condensates, introduced the higher water reduction capacity depending on the electrostatic dispersion mechanism to make higher strength and more flowable concrete. (Rong et al., 2022). The latest generation, polycarboxylate ether (PCE) superplasticizers, in addition to using the electrostatic repulsion mechanism, use the mechanism of steric hindrance to achieve better dispersion of the particle, good slump retention, and good rheological control. This evolution has seen the popularization of the use of high-performance concrete, self-compacting concrete, and pumped concrete in construction projects that are of a complex nature. (Sambangi et al., 2022).

2.2 The Chemistry and Mechanisms of Activity

Plasticizers and superplasticizers act by dispersing the cement grains and thus reducing the flocculation while improving the flow characteristics. Traditional lignosulphonates and SNF/SMF systems are based primarily on the physical principle of electrostatic repulsion by which the negatively charged polymer chains are adsorbed on the cement particles and push themselves away (Tayyab et al., 2025). In contrast, PCE-based superplasticizers introduce comb-shaped molecular structures that provide steric hindrance that helps to physically block re-agglomeration of particles. This mechanism gives an increased water reduction (sometimes more than 25 - 30%) and an enhanced workability retention at high temperatures (Aghaee, 2025). The effectiveness of these mechanisms, however, depends highly on cement mineralogy, the alkali content, sulfate balance, and fineness to a high degree that compatibility is an important consideration in the field (Ma et al., 2025).

2.3 Effects on the Fresh Concrete Properties

Many experiments prove that workability, slump preservation, pumpability, and efficiency of compaction are very much increased by the addition of plasticizers and superplasticizers. They provide the ability to put concrete in congested reinforcement and large volume concrete pours, resulting in the reduction of segregation and bleeding (Nia et al., 2025). However, variability in the performance is seen very often under elevated temperatures and a long transport time, where quick slump loss and non-uniform rheology can be expected because of interactions between cement admixtures. (Pacheco-Torgal, 2025). Field-based research in hot-climate areas would suggest that while initial slump may be high, retention results would be dosed and compatibility tested, allowing for the importance of quality control to be highlighted in actual applications. (Chica et al., 2019).

2.4 Effects on Properties of Hardened Concrete

By reducing the water-to-cement ratio, and without affecting workability, superplasticizers participate in ensuring higher compressive strength, improved tensile strength, and reduced permeability. Long-term benefits of durability include added resistance to attack by chloride, carbonation, and sulfate. (Danish et al., 2023). However, the literature also calls attention to the fact that these improvements are not automatic and are dependent on the quality of curing, discipline with regard to the mix design, and the chemistry of the cement. Studies have shown that where proper curing is not done or in the case of incompatible (different) cementitious systems, this may lead to inconsistent strength development and potentially increase the risk of shrinkage or cracking. (Sofi et al., 2025).

2.5 Compatibility Challenges

Compatibility between cement and admixtures is one of the most generally reported practical problems. Variations on the composition of cement, especially tricalcium Aluminate C3A content, sulfate balance, and alkali content, have a significant impact on admixture adsorption behavior. (Metwally et al., 2025). Computing inconsistent compatibility could lead to rapid slump loss, delayed/accelerated setting, and variability in strength. Developing construction markets often have more serious compatibility issues, because they also have a greater variation of the quality of cement produced, and not as much routine trial testing may be made, and, thus, performance in service is less predictable, and user confidence is lower. (Rigo et al., 2025).

2.6 Market Trends and Adoption Behavior

Globally, the market has facilitated the shift of plasticizers and superplasticizers from an optional add-in to a standard additive in the production of concrete. Markets like developed markets have a high level

of integration supported by performance-based specifications, quality assurance systems, and domestic manufacturing capability. (Sovetova et al., 2024). The developing economies, unlike their counterpart, have selective adoption based on cost sensitivity, lack of supply chain stability, and low institutional enforcement. Research shows that issues of price fluctuation, import reliance, and variable material availability are often the reasons for a lack of widespread use despite technological superiority. (Ahmed et al., 2025).

2.7 Sustainability and Lifecycle Considerations

Plasticizers and superplasticizers positively contribute to sustainability as they provide the potential to optimize the cement, reduce embodied carbon, and enhance service life by improving durability. They promote the production of high-performance and low-carbon concrete. (Khan et al., 2024). However, it has been proposed in the literature that, in many developing contexts, the benefits of sustainability are secondary to short-term considerations regarding the cost, and lifecycle cost evaluation is rarely included in procurement frameworks. This limits the attainment of long-term environmental benefits. (Raj R et al., 2025).

2.8 Research Gap

Currently available literature is mainly concerned with the performance of plasticizers and superplasticizers in laboratory and chemical mechanisms. Far fewer studies use industry-level adoption patterns, market dynamics, cost behaviour, and stakeholder perceptions to develop construction economies. (Sona et al., 2025). There is a serious dearth of total empirical research on the link between technical perception of performance, economic constraints, supply chain structure, awareness of sustainability, and institutional maturity at the scale of countries. This gap restricts evidence-based policymaking as well as helps strategic industry development. This research contributes to filling this gap by doing an empirical evaluation connecting the use of plasticizer and superplasticizer at the national level in Pakistan. (Amir et al., 2024). By bringing together technical, economic, and institutional perspectives, it bridges the literature that currently exists between the evaluation of the laboratory level towards a systems-level understanding of the dynamics of adoption in a developing construction market.

3 Methodology

This research investigates the theoretical factors, namely technological, economic, sustainability, and institutional factors, that control the adoption of plasticizers and superplasticizers in the concrete industry of Pakistan through a well-designed empirical research structure. (Georgiou et al., 2025). Given the fact that the use of admixture is not only a materials engineering issue, but a market and policy-driven phenomenon, the research is based on a cross-sectional mixed method incorporating quantitative survey evidence and contextual industry interpretation. This integrated strategy allows the research to address and capture the patterns of adoption that are measurable, as well as the underlying decision-making dynamics in real construction environments that influence material selection.

3.1 Research Design and Analytical Orientation

The study has applied a descriptive-exploratory research design done as a cross-sectional survey. The descriptive component measures the current industrial practices, type of products currently on the market, application areas, as well as the performance perception of plasticizers and superplasticizers. The exploratory component concentrates on addressing under-researched aspects relating to the market structure, the cost volatility, the dependency of imports, the perception of sustainability, and the

institutional readiness, which play a significant role in shaping the adoption but are poorly documented in developing construction economies. (Safanelli et al., 2025).

A cross-sectional design was used since the Pakistani construction materials market is in a dynamic situation of technological diffusion and price fluctuations, so taking a time-bound snapshot of the industry situation will provide evidence which would be relevant for the policymakers (Abbas et al., 2025). Unlike laboratory-based studies, referring to focusing on material behavior based on controlled conditions, this research focuses on industry-related scale behavioral adoption to which the most appropriate methodological pathway is empirical analysis based on surveys.

3.2 Scope Coverage of Population and Stakeholders

In this study, the target population was professionals and organizations directly related to the production of concrete, design, supply, regulation, and execution of projects in Pakistan. These included structural consultants, contractors, ready-mix concrete producers, chemical admixture producers, project developers, academicians, and professionals linked with regulatory or professional institutions. Collectively, these stakeholders make up the entire concrete value chain and have a practical influence on admixture specification, procurement, and application decisions. Capturing perspectives from multiple stakeholder categories is important to ensure that the understanding of the adoption behavior is not based on a single technical perspective but on a systemic industry perspective, and this is necessary when studying materials whose use is determined as much by economics and institutional set-up as by performance parameters.

3.3 Sampling Strategy and Sufficient Sample Size

In view of the absence of a national sampling frame and the technical specialization of the respondent population, a stratified purposive sampling technique of sampling was followed. Regarding the relevance to the professions and many years of experience in concrete technology and/or material decision-making, respondents were chosen (Wu et al., 2024). Stratification by consultants, contractors, suppliers, producers, and regulators reduced the question of sectoral bias and enabled comparison by these categories across the board. (Zhao et al., 2025). A total of 381 valid responses were obtained and used for analysis. This sample size is larger than the sample size suggested for descriptive and exploratory surveys, which are usually carried out in the construction sector, and is with sufficient statistical stability for mean index calculation, comparative analysis, and perception-shaping modelling. The relatively large sample also helps to reduce the effects of non-response bias and helps to enhance the trend in the industry-level scores. (Vishwakarma et al., 2023; Zhao et al., 2025).

Primary data was collected using a structured questionnaire, which was developed using a multi-stage process. First, an international literature on chemical admixtures, market adoption models, and sustainability-driven material selection was reviewed in order to identify key constructs. Second, secondary market data about pricing, import dependency, and application trends were reviewed for putting local situation in perspective. Third, industry professionals were consulted when the instruments were drawn up to make sure they were relevant in practice. (Wang et al., 2025). The final questionnaire was designed with thematic areas linked to the characteristics of the respondent, types of admixture, areas of application, perceived performance of the technical performance, economic and marketing constraints, perceived sustainability, and future outlook. Most of the variables related to perceptions were assessed in a five-point Likert scale to standardize attitudes to be quantified and so that the results could be statistically compared. (di Summa et al., 2022). Pilot testing with industry professionals helped

to ensure context clarity and appropriateness. Minor refinements were introduced to overcome the ambiguity and also to ensure that it is in tune with the construction practices in Pakistan.

3.4 Structure of Conceptual Variable

The analytical framework of the study accepts admixture adoption as a function of interacting technical and non-technical variables. Some of the technical variables are workability improvement, slump retention, strength development, durability improvement, and compatibility. Market variables are the cost perception, price trends, availability, and import dependency. Sustainability variables lie heavily with academic concern with the reduction potential in cement and the performance of cement in a life cycle period. (Hai et al., 2025). Institutional variables have to do with regulatory support, standards, and industry awareness. These independent dimensions jointly influence the behaviour of, among other things, adoption, economic viability, as well as the prospects for growth in the future, which are dependent outcomes. This structure allows for a techno-economic sustainability integration model as opposed to just a performance-based evaluation.

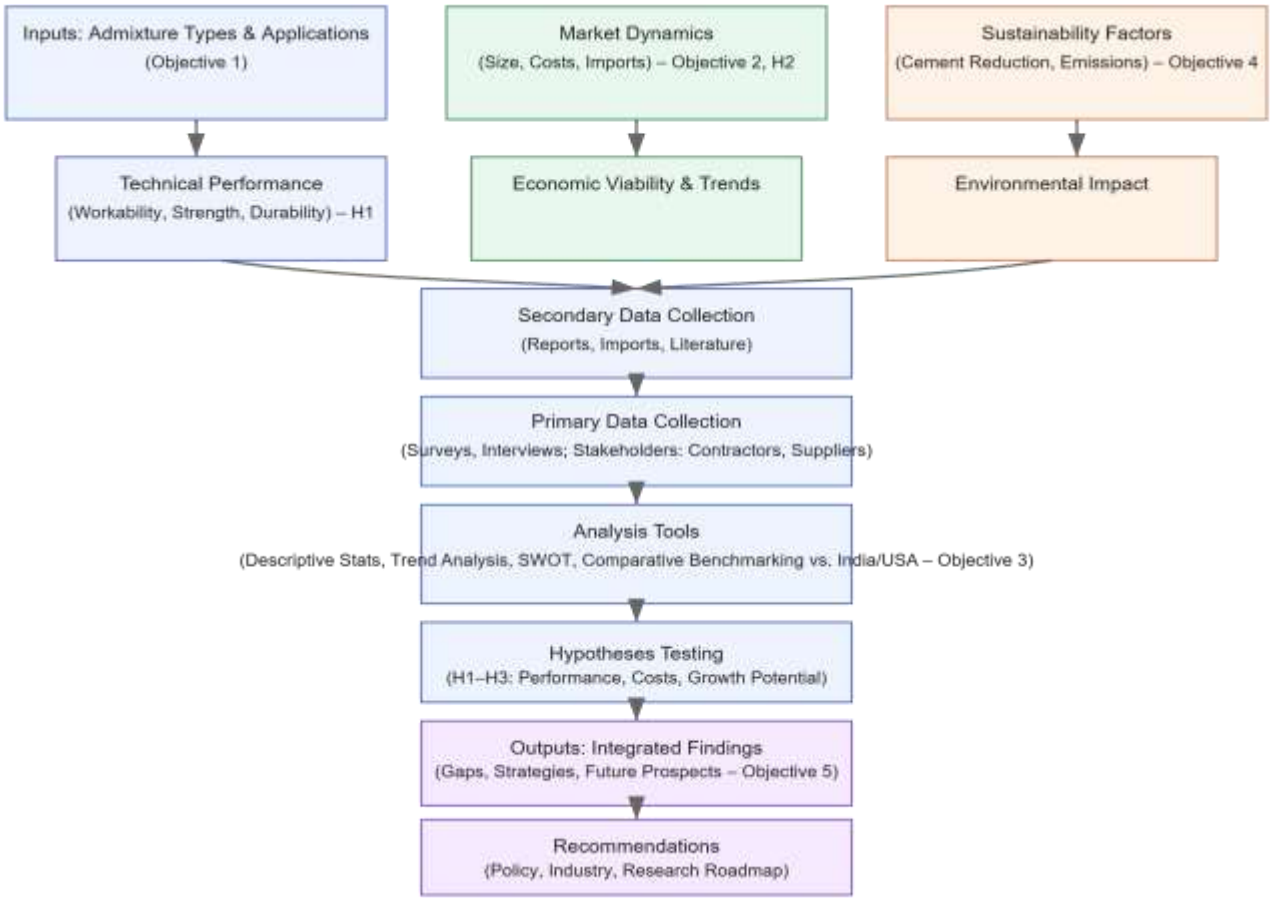

Figure 1: Research Model

3.5 Data Analysis Procedures

Quantitative survey data have been analysed with descriptive statistical tools such as frequency distribution, percentage analysis, mean score indexing, and standard deviation. Mean index analysis was performed to rank the technical and market factors, based on the perceived importance (Carmona-

Ramírez et al., 2025). Cross-tabulation enabled to compare the way between stakeholder groups, mainly in terms of cost-sensitivity and perception of performance. Graphical representation was used for the visualization of application patterns and the severity of constraints. International benchmarking has been done qualitatively through comparison of the state of adoption in Pakistan to established markets in order to help contextualize findings. Qualitative inputs of open-ended responses and expert consultations were thematically interpreted to explain statistical trends. Finally, an integrated analytical synthesis was conducted that investigates the interaction of the comparative advantages of performance, cost volatility, and supply risk, as well as institutional maturity, to explain the results of the adoption.

3.6 Validity, Reliability, and Research Rigor

Content validity was ensured by linking items in the questionnaire with the known literature constructs and research goals. An expert review was used to check the coverage of the constructs and context relevance. Construct validity was improved by having multi-item measures of each variable. (Manso-Morato et al., 2024). Internal consistency reliability was conducted as a pilot phase by testing Cronbach's Alpha with coefficients above an acceptable level (alpha greater than or equal to 0.70) that demonstrate reliability for the measurement of the perceptual constructs. Triangulation between survey findings, secondary market data, and expert interpretation also helped to increase research rigour. (Nayak et al., 2022). Participation was voluntary, and the respondents were told about the academic aim of the study. No pursuit of personally identifiable information was imputed. Data was analyzed and reported in aggregate forms only, and confidentiality was ensured, and research ethics followed.

4 Results and Discussion

4.1 Dataset and Respondent Credibility

The empirical analysis is based on 381 valid responses that were obtained from a wide array of players of the concrete value chain in Pakistan, such as contractors/builders, consultants/design engineers, Ready Mix Concrete (RMC) Plant Managers, suppliers' technical managers, clients/developers, regulators, and academics. The respondent profile demonstrates professional relevance as well as coverage of the U.S., which enhances the credibility of the results.

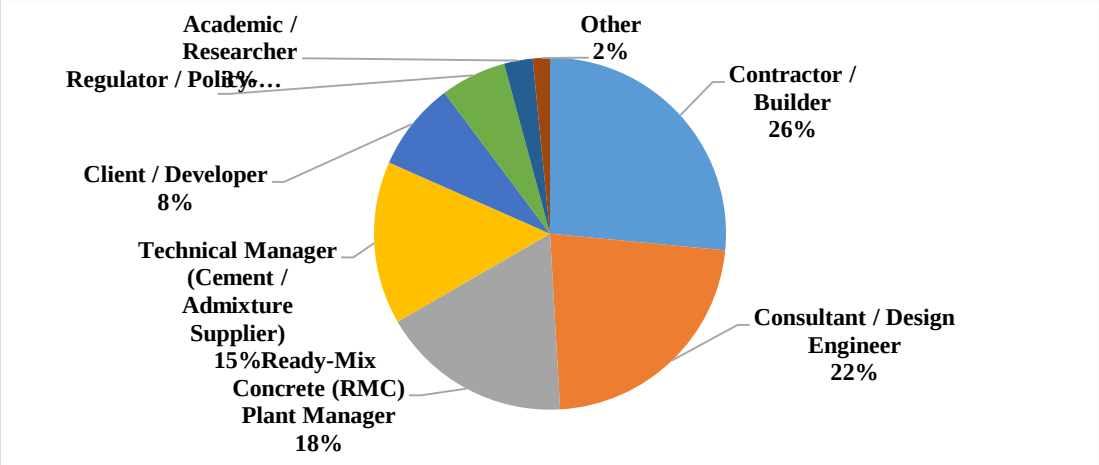

Figure 2: Distribution of Respondents by Professional Role

The representation of such core decision-makers, especially contractors, consultants, and RMC managers, is important as they have a direct bearing on mix selection, admixture dosing practice, batching discipline, and acceptance of performance outcomes on-site.

Table 1: Primary Project Type Involvement of Respondents

Sr No	Primary Project Type	Frequency
1	High-rise residential/commercial buildings	28
2	High-rise residential/commercial buildings & small-scale housing	23
3	High-rise residential/commercial buildings & infrastructure projects	19
4	Industrial structures (factories, warehouses)	19
5	High-rise residential/commercial buildings & industrial structures	14
6	Roads and highways	13
7	Infrastructure (bridges, dams, flyovers, tunnels)	12
8	Precast concrete elements	11
9	Small-scale housing projects	10
10	Mixed project portfolios (multiple sectors)	Remaining cases
Total		**381**

Sector exposure is also diverse, with respondents saying that they were involved in high-rise construction, infrastructure works, industrial projects, roads/highways, precast production, and mixed portfolios. This is important since admixture value can often be context dependent - in congested reinforcement, high flow concrete for slump maintenance, durability expectations in aggressive environments, and early handling strength requirements in precast.

4.2 Market Penetration and Intensity of Use

The results confirm that plasticizers and superplasticizers are no longer in use in "niche" applications, but have now been enshrined in the mainstream. The total number of respondents in using plasticizers or superplasticizers in the last 24 months was 307 out of 381 respondents, which is 80.6%.

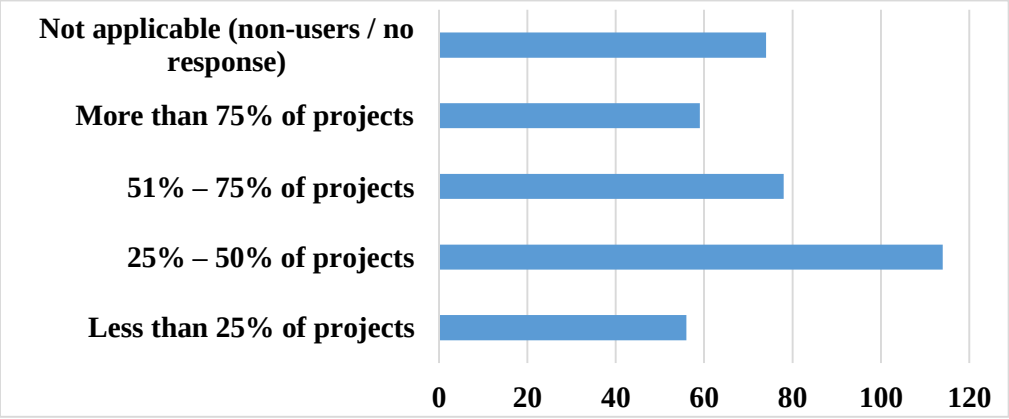

Figure 3: Extent of Use of Plasticizers and Superplasticizers Across Projects

This degree of recent use is high for a developing market and is an indication of the use of admixtures as a practical tool to control workability, constructability, and performance requirements under Pakistani site conditions. However, the level of adoption is not uniform. The distribution of usage in different projects shows that while some professionals have admixtures in the majority of their projects, even here, it is not negligible the percentage that utilizes admixtures in a selective way (sometimes 25-50% of projects) that corresponds to the co-existence of modern RMC-led construction and more traditional construction practices constrained by economic considerations. This duality becomes central later for the interpretation of the fact that technical acceptance is not equal to universal adoption.

4.3 Perceived Technical Performance: Reliable vs. Fragile Aspects

In order to test the technical hypothesis (H1), five core performance dimensions were tested using 5 point Likert scale. Because performance ratings were only provided by the respondents with appropriate exposure, valid ratings are n = 307 (74 ratings were missing/not applicable). This structure itself is revealing: in the sense that about one-fifth of the total sample either did not use admixtures, or did not feel confident in ratifying technical outcomes, this adds to the character of the market as "partial institutionalization".

4.3.1 Workability: The Most Consistent Performance Benefit

Workability improvement is displayed in the most accordance and consistency in the data set. The valid responses obtained were: 58.9% agreed/strongly agreed on the fact that plasticizers/superplasticizers affect workability, with 45.3% agreeing and Strongly Agree 13.7%, while disagreements were low (6.8%), and 34.2% is Neutral. The mean score is 3.66 (SD 0.80). This pattern shows that the chief "felt" value of admixtures by the industry in Pakistan is on the constructability, a value that is immediate and visible in nature. The neutral segment is not rejection, rather an indication of the ability to dilute beneficial factors due to field realities like unregulated water addition, variation of water content of the aggregate, poor slump monitoring, or lack of discipline in batching. Importantly, the absence of "strongly disagree" responses (0%) suggests that outright failure of workability improvement is rare; where it occurs, it is likely to have something to do with errors in dosing or compatibility issues rather than the effectiveness of admixture mechanisms more generally.

4.3.2 Slump Retention: A Key Reliability Risk

Slump retention differs very differently. Neutral answers are the best (45.3%), with relatively low numbers of people saying (Agree 26.1%, Strongly Agree 2.6%) and a great percentage of people saying (26.0%, Disagree 23.1% + Strongly Disagree 2.9%). The average score is 3.02 (SD 0.85) and is virtually on the edge of neutrality.

Table 2: Mean and Standard Deviation of Technical Performance Indicators

Sr No	Parameter	Mean	Std. Dev.	Interpretation (MSc-level)
1	Workability improvement	**3.66**	0.80	Strong positive perception, relatively consistent
2	Slump retention	**3.02**	0.85	Borderline neutral; performance perceived inconsistent.
3	28-day compressive strength	**3.49**	0.71	Moderately positive; conditional on mix control
4	Durability enhancement	**3.15**	0.79	Mild positive; under-recognized due to limited testing
5	Cement compatibility	**2.92**	0.97	Below neutral; the highest variability and key barrier

This is a significant result because it is shown that in real field operations, there is a challenge to reliability with respect to concreting in hot weather, as well as in countries like Pakistan of relevance to hot weather concreting and long time of transportation and variable cement chemistry. The very low strong agreement (2.6%) suggests that a relatively low proportion of practitioners have consistently good retention, typically where the controls in batching, admixture selection, dosage optimization, and quality assurance would be more potent. In the context of a journal paper, this is a high-value insight, because slump retention is not a material property but instead on a "system performance" level, dependent on the maturity of the supply chain and process.

4.3.3 Conditional Nature of Strength Improvement in Field Practice

Perception of the development of compressive strength in 28 days, the industry rarely considers the possibility that the effect of admixtures has an influence on the strength (combined disagreement 5.5%), but the industry does not perceive the development of strength as a guarantee. Neutral perceptions are high (46.3%), and moderate is the degree of agreement (Agree 42.0%, Strongly Agree 6.2%). The mean score is 3.49 (SD 0.71). This distribution gives a powerful argument in favor of the practical interpretation: improvement of the strength is usually indirect (by water reduction and better dispersion) and is only visible if water-cement ratio control, curing discipline, and testing verification are available. In applications where the introduction of site water along with variation in curing is commonplace, the strength strength improvement then becomes spotty with respect to perception, even if it is technically possible. The data set therefore supports H1 and additionally supports a condition of implementation required for admix potential to lead to measurable strength outcomes.

4.3.4 Under-Recognition of Durability Benefits Due to Limited Measurement Practices

Durability enhancement has the widest scope of "verification gap" in the technical set. Nearly half of the respondents are neutral (47.9%) with a low level of agreement (Agree 28.3%, Strongly Agree 3.6%) and a low level of disagreement (Disagree 20.2%, Strongly Disagree 4.7%). The mean score is 3.15 (SD 0.79). This is not to say that admixtures do not enhance durability; it is an indication that durability is not tested, prescribed, or monitored in routine Pakistani projects, and therefore the professionals do not get a chance to see results of performance in real life. In journal language, the problem this corresponds to is a "measurement-visibility problem" where workability is easily visible, strength is visible with testing,

and durability is visible only with long term monitoring and performance metrics, which are not necessarily institutionalized by the local construction culture. This gap is also consistent with the subsequent findings regarding the sustainability as well (i.e., sustainability is recognized but not as a driver of decision-making).

4.3.5 Compatibility-Driven Variability in Technical Performance

Compatibility with cementitious materials turns out to be the most important technical constraint. Combined negative responses are high (33.5%, Strongly Disagree 6.5% + Disagree 27.0%), not to mention neutrality is also high (39.4%), and positive agreement is limited to 27.1%, Agree 22.5% + Strongly Agree 4.6%. The average score is 2.92 and has the greatest standard deviation (0.97) of all parameters, which means that they are experiencing a low average confidence level and high dispersion in experience. This is the best interpretation of the data in your dataset, showing that the admixture performance in Pakistan is actually limited because not only does the product itself lack availability, but the matter variability and insufficient systematic testing compatibility of the matter appear to be an issue. Importantly, compatibility is the technical explanation that brings not only multiple observations together: it helps to explain slump retention inconsistency and scattered strength perception and selective adoption behaviour, in spite of obvious workability advantages. In a journal manuscript, compatibility becomes the "mechanism-level" bottleneck on policy and standards to fix.

4.4 Comparative Reliability Assessment of Performance Parameters

In order to give higher interpretability as compared to mean scores, result of the study can be given in terms of Net Agreement (NA), which is (Agree + Strongly Agree) - (Disagree + Strongly Disagree) for each parameter. This converts Likert distributions into a useful "signal strength" distribution that is easy for the reader to understand.

Table 3: Net Agreement and Reliability Ranking of the Technical Outcomes

Technical parameter	Agree + Strongly Agree (%)	Disagree + Strongly Disagree (%)	Net Agreement (%)	Mean ± SD	Reliability interpretation
Workability improvement	58.9	6.8	**+52.1**	3.66 ± 0.80	Strong and consistent benefit
28-day strength	48.2	5.5	**+42.7**	3.49 ± 0.71	Conditional benefit; rarely negative
Durability enhancement	31.9	20.2	**+11.7**	3.15 ± 0.79	Under-verified; visibility gap
Slump retention	28.7	26.0	**+2.7**	3.02 ± 0.85	Operationally fragile; inconsistent
Cement compatibility	27.1	33.5	**−6.4**	2.92 ± 0.97	Structural barrier; highest variability

This table does two things, which makes the acceptance probability stronger. First, it certainly indicates that the technical "value proposition" is dominated by workability and then conditional strength benefits. Second, it shows that slump retention is almost "neutral" in net signal, and compatibility is the only parameter with a negative net agreement, which means barriers do not exist anecdotally, they are statistically visible.

4.5 Role-Based Variations in Technical Perception

Role-wise mean scores provide a second layer of evidence and reduce the possibility of over-generalization. Workability improvement is generally high through out the roles, with the highest being regulations (3.89) and RMC plant managers (3.75), who apparently have the best awareness of the benefit amongst the stakeholders closer to performance and batching discipline.

Table 4: Role-Wise Mean Scores – Workability Improvement

Sr No	Professional Role	Mean Score	Valid Responses
1	Regulator / Policy-maker	3.89	19
2	Ready-Mix Concrete (RMC) Plant Manager	3.75	56
3	Consultant / Design Engineer	3.66	73
4	Contractor / Builder	3.65	78
5	Technical Manager (Cement / Admixture Supplier)	3.53	45
6	Client / Developer	3.50	24
7	Academic / Researcher	3.29	7

Slump retention rating remains around neutral across the different roles with the contractors and supplier technical managers with slightly higher ratings of 3.18 each, whereas the academics rate lowest at 2.86, suggesting that practitioners may perceive that retention may be effective under certain conditions, the technical observers remain cautious due to inconsistency.

Table 5: Role-Wise Mean Scores – Slump Retention

Sr No	Professional Role	Mean Score	Valid Responses
1	Contractor / Builder	3.18	78
2	Technical Manager (Cement / Admixture Supplier)	3.18	45
3	Ready-Mix Concrete (RMC) Plant Manager	3.07	56
4	Consultant / Design Engineer	3.07	73
5	Regulator / Policy-maker	3.05	19
6	Client / Developer	3.00	24
7	Academic / Researcher	2.86	7

Differentiation between perception of strength is more noticeable: the value of the benefits of strength students measured in academia and regulation is higher than for contractors and also for consultants (3.41 each).

Table 6: Role-Wise Mean Scores – 28-Day Compressive Strength

Sr No	Professional Role	Mean Score	Valid Responses
1	Academic / Researcher	3.86	7
2	Regulator / Policy-maker	3.74	19
3	Client / Developer	3.58	24
4	Ready-Mix Concrete (RMC) Plant Manager	3.55	56
5	Technical Manager (Cement / Admixture Supplier)	3.44	45
6	Consultant / Design Engineer	3.41	73
7	Contractor / Builder	3.41	78

This trend is consistent with the previous conclusion that strength benefits are better appreciated where testing and controlled evaluation are the norm. Durability is of a moderate level for each of the roles,

and again the highest for the group of academics with a durability score of 3.57, which reinforces the idea that durability recognition is linked to the culture of measurement and not to the visibility in the field.

Table 7: Role-Wise Mean Scores – Durability Enhancement

Sr No	Professional Role	Mean Score	Valid Responses
1	Academic / Researcher	3.57	7
2	Contractor / Builder	3.18	78
3	Technical Manager (Cement / Admixture Supplier)	3.18	45
4	Client / Developer	3.17	24
5	Ready-Mix Concrete (RMC) Plant Manager	3.16	56
6	Consultant / Design Engineer	3.10	73
7	Regulator / Policy-maker	3.00	19

Most importantly, there is little cement compatibility among each type of stakeholders; there is no more than a mean of 3.08 roles. Consultants have the lowest mean for compatibility (2.75),alsos this is interesting because consultants often are saddled with explaining to clients the variable nature of performance and diagnosing site problems. The fact that the scores of low compatibility are cross-role stable is good evidence from a journal point of view that compatibility is not a localized perception which must be altered by one group or the other, much less that it is a perceived constraint throughout the system.

4.6 Market and Cost Dynamics Influencing Adoption

The results coming from the market test are consistent with Hypothesis H2, where easy to understand quantitative signals. Import dependency is high: almost 80% of the respondents are dependent on imports or a partly imported admixture supply chains, while only 20.2% said that they use pure local products.

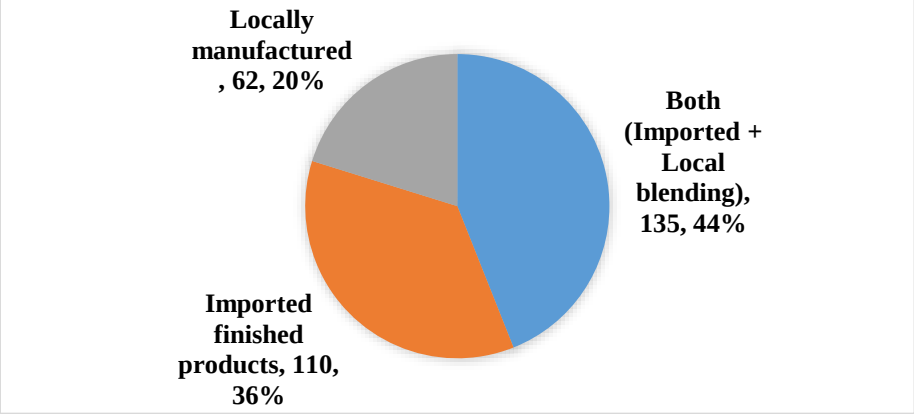

Figure 4: Source of Plasticizers and Superplasticizers Used in Pakistan

This structure leaves the market to the exchange rate shocks and the disruptions in logistics, and it is good to understand why price volatility is so prevalent in the economic story. Price trends heavily upwards: a majority (estimated 87 per cent) of the respondents indicate that the prices of foodstuffs have increased moderately to a lot over the last three years.

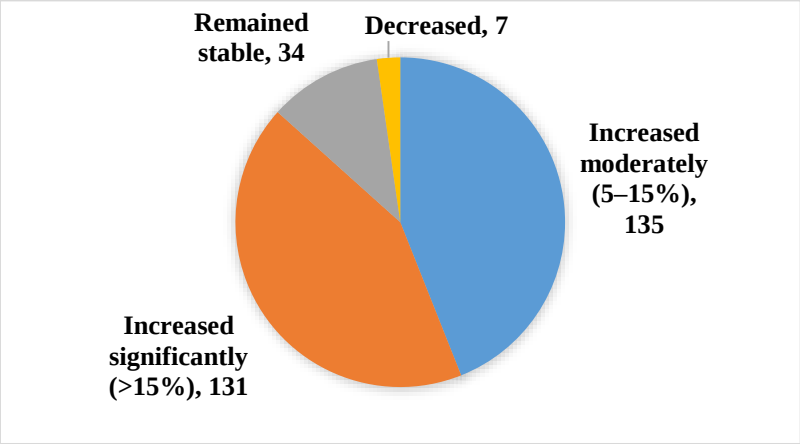

Figure 5: Perceived Price Trend of Plasticizers and Superplasticizers (Last 3 Years)

Such inflation, in the context of cost-sensitive procurement, opens up a predictable value engineering path with the admixtures being an optional extra even in cases where the ingredients can be very useful, actually.

Supply chain restriction is also visible. While 55.7% of them say that they face no major challenges (thus suggesting that larger firms with more developed procurement systems can buffer the risks), the rest say that price volatility and import delays are recurrent constraints.

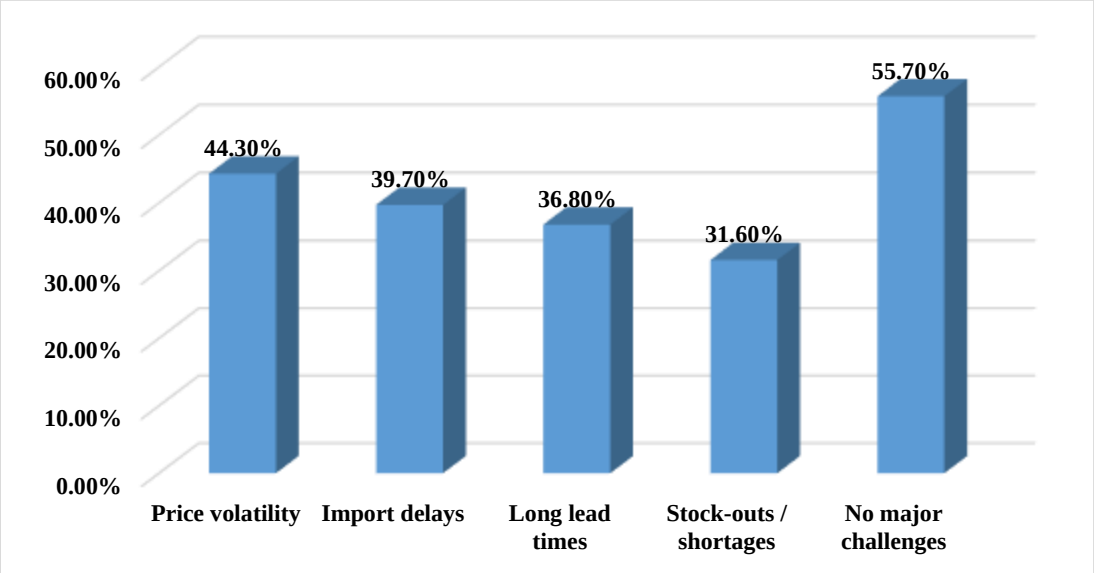

Figure 6: Reported Supply-Chain Challenges

Market size estimates are concentrated generally around 5,000 to 20,000 tons/year, although it is clear that the wide range itself is indicative of a lack of official reporting on the market, an evidence-based justification for your paper based on the market focus. With current limitations, the forecasts are quite optimistic: more than 3 quarters of the respondents project moderate to fast growth of demand in the next five years, and this is consistent with the "suppressed demand" interpretation in which technical acceptance is achieved, but economic instability restricts growth.

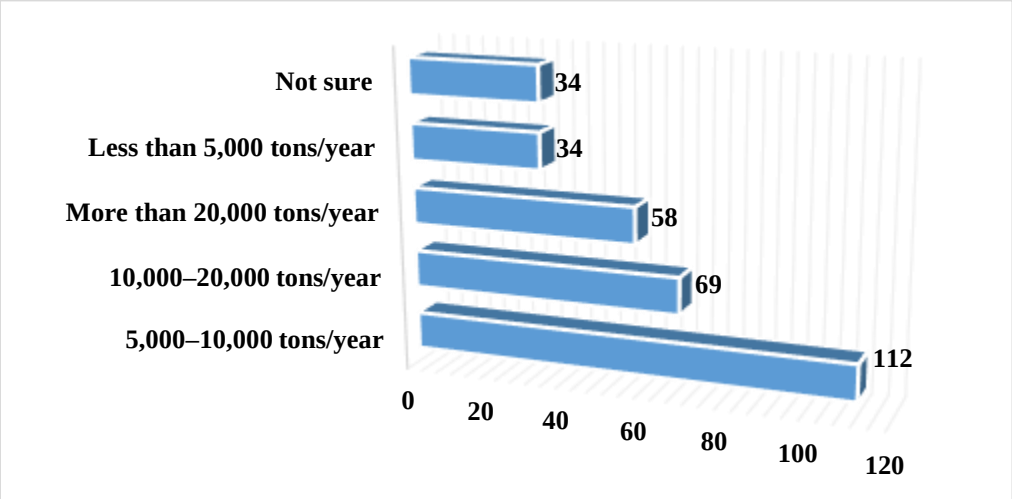

Figure 7: Estimated Market Size of Plasticizers and Superplasticizers in Pakistan

The dataset is corroborative to cost competitiveness issues: About 57% believe that admixtures are more expensive than alternatives, which reflects part of the reason for selective adoption being a feature of small-scale housing, low margin projects, and where short-term cost is more important than lifecycle value.

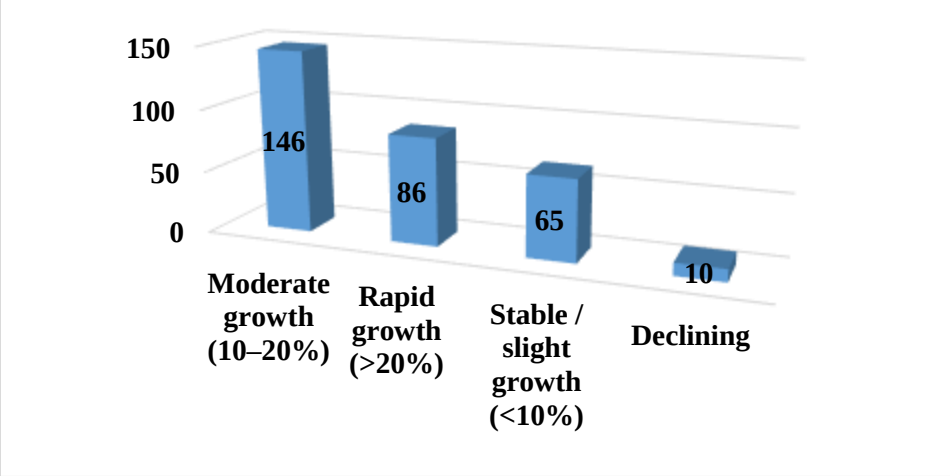

Figure 8: Expected Change in Admixture Demand over the Next Five Years

More than three-quarters of respondents predict a moderate to fast pace of demand for admixture products due to the increase in levels of urbanization, infrastructure, and performance-based construction requirements. This optimistic outlook stands in strike to cost issues at present, when, & suggests latent demand being suppressed by economic constraint than a lack of technical acceptance.

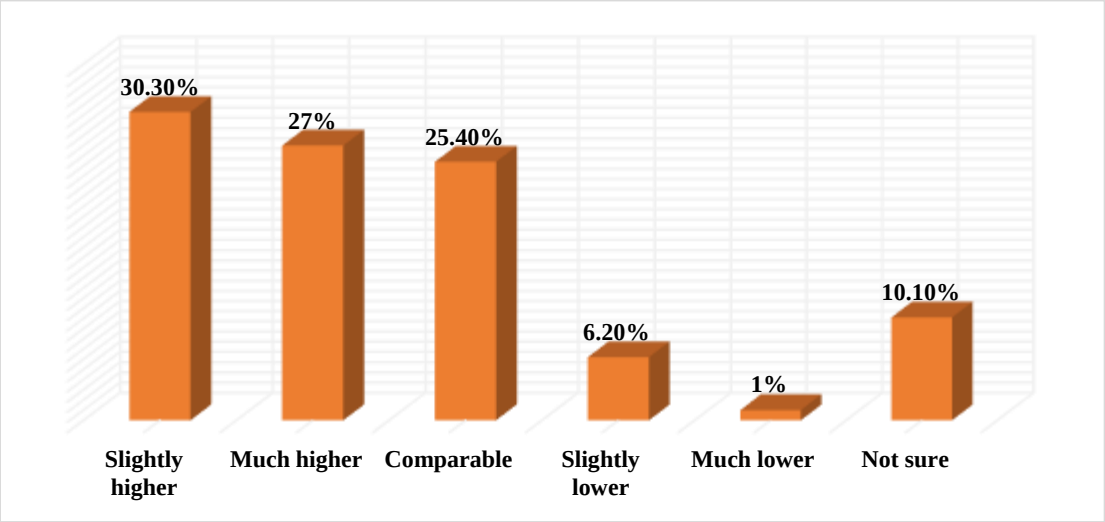

Figure 9: Price Competitiveness of Plasticizers Compared to Alternative Solutions

Nearly 57% of the respondents looked at admixtures to be more expensive than other practices (e.g., increased cement content, site water adjustment). This perception prevents the adoption of admixtures that have the potential of improving life cycle performance.

Table 8: Cost Perception of Plasticizers by Professional Role (%)

Sr No	Professional Role	Much Lower	Slightly Lower	Comparable	Slightly Higher	Much Higher	Not Sure
1	Academic / Researcher	0.0	14.3	14.3	57.1	14.3	0.0
2	Client / Developer	0.0	4.2	37.5	20.8	**33.3**	4.2
3	Consultant / Design Engineer	0.0	1.4	20.5	35.6	**35.6**	6.8
4	Contractor / Builder	1.3	3.8	29.5	28.2	24.4	12.8
5	RMC Plant Manager	0.0	10.7	21.4	32.1	23.2	12.5
6	Regulator / Policy-maker	5.3	5.3	21.1	36.8	21.1	10.5
7	Technical Manager (Supplier)	0.0	13.3	28.9	20.0	24.4	13.3

Table 8 shows some of the clear and systematic differences between professionals in terms of cost perception: Of these, the consultants and the academics have the most negative perception of high cost, with more than 70% of consultants judging admixtures to be slightly or much more expensive. This is a reflection of their orientation to specification compliance and up-front project costs. Clients and developers are price sensitive, with one-third of them feeling that different pricing of admixtures is really higher priced, indicating resistance where lifecycle benefits are not explicitly quantified.

Contractor- and RMC plant-related views: - Contractors and RMC plant managers are more balanced about the issue, with a significant percentage rating prices as comparable - this is presumably a result of familiarity with operation and cost optimization through volume purchasing. The results for the remaining market segments are: - Suppliers display relatively neutral perception: this is unsurprising, seeing as they have knowledge of cost structures and margins. Cost perception is not across the industry; it is a role-dependent concept. This explains why adoption decisions vary even in the case of commonly recognized technical benefits.

Table 9: Adoption Barrier Matrix for Plasticizers and Superplasticizers in Pakistan

Barrier Dimension	Keys Values	Nature of Risk to Adoption	Risk Level	Systemic Impact	Targeted Intervention
Cement–Admixture Compatibility Issues	33.5% negative responses; Mean = 2.92; Highest SD	Inconsistent performance, slump loss, setting variability, and strength scatter	**High**	Reduces practitioner confidence; leads to selective rather than routine use	Pakistan-specific compatibility standards; Prequalification testing protocols; Localized technical guidelines
Slump Retention Variability	26% negative responses; Mean = 3.02	Loss of workability during transport; re-tempering with water; site quality issues	**High**	Directly affects constructability and durability; discourages use in remote or hot regions.	Training & certification of batching operators; Guidelines on retention admixture systems; QA/QC protocols
Import Dependency	~80% imported or hybrid supply chains	Exposure to forex volatility, supply delays, and formulation mismatch with local cements	**High**	Market instability; price shocks; technical mismatch	Incentives for local manufacturing; Support for domestic R&D; Supply chain localization
Price Escalation & Volatility	87% report price increase. Cost perception mean = 3.85	Cost sensitivity in housing & public sector projects; preference for cement over admixtures	**High**	Limits adoption in cost-sensitive projects; suppresses lifecycle optimization	Lifecycle cost–based procurement frameworks; Inclusion of admixtures in public specs; Fiscal incentives

Low Awareness of Best Practices	~85% low–medium awareness	Improper dosage, lack of compatibility testing, and misuse on-site	**Medium–High**	Amplifies technical risks; widens performance variability	National training programs; CPD certification; Dissemination of international standards
Under-Recognition of Durability Benefits	Neutral dominance (47.9%); Mean = 3.15	Short-term focus; neglect of long-term performance gains	**Medium**	Sustainability potential is not translated into decisions	Durability-based design codes; Performance specifications; Awareness programs
Selective Project-Level Adoption	Majority use in 25–50% of projects	Uneven diffusion across the industry	**Medium**	Fragmented market penetration	Institutional standardization; Public sector mandates

The above table synthesizes the results of the study to come up with a holistic risk model for the current state of play of the use of plasticizers and superplasticizers in Pakistan, in the form of their technical acceptance and uneven implementation. The matrix identifies barriers to adoption as not isolated but systemic and falling into three different domains, which interlink: technical reliability, economic exposure, and institutional capacity.

Technical risks are dominated by problems with the compatibility of cement admixture (mean = 2.92) and the variability of slump retention (mean = 3.02), which create a lack of predictability of performance and practitioner confidence. Economic risks of having high import dependency and a continued price increase that makes admixtures vulnerable to currency fluctuations and a lack of stability in their supply chain to use in cost-sensitive applications. Institutional risks, including a lack of knowledge of best practices and a relative lack of recognition of the advantage of durability, are multiplying the technical and economic constraints greatly by compromising quality control and lifecycle-based decision-making.

As the table shows, adoption issues are not associated with a lack of technical benefits (workability and strength improvement are recognized) but with risk perception associated with performance inconsistency, price fluctuations, and lack of institutional support. By identifying each barrier to specific interventions (such as local standards, compatibility testing protocols, training programs, and incentives for domestic manufacturing), the matrix turns empirical findings into a framework for specific action for development.

4.7 Techno-Economic Adoption Gap

A defining contribution of your thesis is the integrated techno-economic analysis in Section 4.6, which is defined as changing from descriptive reporting to an explanatory model. A composite Technical Performance Index (TPI) was developed using the workability, strength, durability, and compatibility ratings, and cost perception was measured in order to allow for joint interpretation. The results indicate that even if we only consider cases with valid answers (n=276) mean TPI is 3.28 (SD 0.40), whereas the mean cost perception score is 3.85 (SD 0.97). This is a powerful discrepancy from an analytical

perspective: We find that respondents emphasize that performance is positively rated on average, but at the same time, that admixture is valued as costly-that is, that the adoption choices are moderated based on economics and not by performance.

Table 10: Descriptive Statistics of Techno-Economic Variables

Sr No	Variable	Mean	Std. Dev.	Min	Max
1	Technical Performance Index	3.28	0.40	2.25	4.50
2	Cost Perception Score	3.85	0.97	1.00	5.00

(Valid cases = 276 respondents)

This explains the earlier actualization of the saw behavior: On the one hand, with a high level of recent usage (80.6%), there is also selective penetration for the project. In practice, it would seem that the Pakistan admixture market is on the way from "problem-solving use" (use when needed for workability or constructability) to "institutionalized use" (use as part of standard specifications). The transition is suggested to be blocked by two structural mechanisms: on the one hand, price and supply instability of the import dependency; on the other hand, risk predictability issues of the inconsistency of compatibility. Together, they offer the ambience of adoption where admixtures are accepted but not quite normalised. This mechanism is further supported by the cross-tabulation. Cost perception varies tremendously based on the status of the person who will be affected. Consultants have the greatest perception of "high cost" with admixtures, a slightly or much higher rating by 71.2%. Clients/developers are also hypersensitive with the latter feeling, with 54.1% of them reporting costs being slightly to much higher (20.8% + 33.3%). In contrast, the perceptions of contractors and RMC managers are more balanced, and they have higher shares (in proportion) of "comparable" (contractors=29.5%, RMC managers=21.4%). This role effect is critical in that the groups that usually specify or approve material costs (i.e., at design/procurement stages) are more likely to consider admixtures as expensive, thereby increasing the likelihood of value engineering, even if the technical benefits are appreciated by field practitioners. This makes a very clear and defensible explanation as to why there is not a uniform market penetration.

4.8 Institutional Maturity Lags Behind Sustainability Awareness

Sustainability findings support Hypothesis H3 but also suggest that sustainability is currently a subsidiary to cost. More than 70% of the respondents recognize sustainability to be either the main driver or a supporting driver of admixture decisions, but only 11.7% of them mark sustainability as the main driver for admixture decisions, while 59.3% mark sustainability as a secondary driver. This measures a state of affairs that is very much the case in the developing markets: the sustainability is there in awareness and not in purchasing power. Strong growth expectations of future admixture demand suggest that, above all else, passengers associate admixture use with efficiency and lifecycle performance, even if they are not already quantifying this in formal sustainability metrics.

Table 11: Ranked Policy Interventions Required for Market Development

Rank	Policy / Regulatory Intervention	Frequency	Relative Priority
1	Development of Pakistan-specific standards and guidelines	116	Very High
2	Training and certification programs for engineers	91	High
3	Incentives for local manufacturing	83	High
4	Inclusion in public works specifications (e.g., PSDP, CPEC)	81	Moderate–High

The institutional evidence would explain the weak evidence of moving from awareness to standardised practice. About 85% of the respondents are the low to medium awareness of international best practices and guidelines. This is in agreement with the technical results, when compatibility and slump retention are weak: As long as the guiding principles are not standardized, trial mix culture and training systems are absent, resulting in a lack of consistency in mix results and a high level of risk perception. Policy ranking results show unanimous agreement on what needs to be done: Pakistan-specific standards and guidelines ranked highest (frequency 116-117, followed by training/certification (91; 89) and incentives for local manufacturing (83; 97). The meeting of two ranking questions lends deference to this policy story that institutional reform is the clarion call to bring the possible to technical potential, actual implementable scales of practices.

Taken as a whole, the results provide good empirical evidence of the three hypotheses with publication-grade enhancements. Hypothesis H1 is supported because workability (mean 3.66) and strength development (mean 3.49) are perceived as positive (but clearly prove to be conditional: slump retention is not able to consistently (mean 3.02), and cement compatibility is constraint of systemic (mean 2.92)). So hypothesis H2 is strongly supported due to import dependency (~80%) and price escalation (~87%) imply adoption limit found that is supported by techno-economic gap (TPI 3.28 vs cost score 3.85), and also, role-driven is cost sensitive. Hypothesis H3 is supported in the sense that it is widely recognised (> 70%), but that this effect is, in any case, still moderated by the shortness of time it takes to make economic decisions and the lack of institutionalisation of lifecycle metrics.

5 Conclusions and Recommendations

This study is one of the most comprehensive empirical evaluations based on responses from 381 professionals in the construction value chain of Pakistan, based on the use of plasticizer and superplasticizer in the concrete industry. The findings validate a shift from technical skepticism to the widespread acceptance and use of chemical admixtures in performance-based construction, such as high-rise buildings, ready mix operations, and infrastructure projects (more than 80% of respondents report recent use). However, widespread and consistent adoption is limited by a combination of variance on a technical level, economic exposure, and institutional gaps.

Technically, workability improvement is viewed to be the best and consistently experienced assignment improvement, while strength improvement is experienced as positive and known as a conditional attribute that depends on the use of correct mix control and curing practices. Durability Benefits Although scientifically established, in the field, the benefits of durability are under-recognised through a lack of monitoring of performance. Cement--admixture compatibility was found to be the most significant technical problem, having the least mean and most variance in the results obtained, which indicated an inconsistency in the material and the absence of systematic compatibility testing protocols. Economic analysis leads me to conclude that it is market structure, not technical skepticism, that is the biggest limiting factor in wider adoption. High dependency on import price fluctuations and a persistent rise in cost. This was what most of the respondents pointed out and defines a techno-economic gap in which the perception of technically effective materials is still that of being expensive. This self-imposed short-term focus on costs in particular restricts use for small-scale and public projects in spite of known lifecycle benefits. From a sustainability perspective Awareness with regard to the environmental benefits of admixtures - it is true that the potential of admixtures to reduce cement consumption, durability, and the life-cycle of infrastructure remains on the rise, but sustainability is also a secondary factor behind

the cost considerations. A failure of strong formal integration of durability and lifecycle indicators in the design and procurement frameworks is a constraint on commitment to the technical potential of measuring environmental performance.

Institutional lack of Pakistan-specific standards, lack of awareness of best practice, and low technical capacity are some of the factors that contribute to variance in performance and risk-averse adoption behaviour. Stakeholders strongly advocate for localised standards, well-structured training programmes, and incentives for local manufacturing as some of the most important enablers for market stabilisation and technological maturity. Accordingly, the multi-level approach is proposed by the study. Regulatory authorities should set up Pakistani-specific admixture standards, such as compulsory compatibility testing and performance-based durability criteria, etc. Industry-wide training and certification programs are needed in the industry to reduce variability and improve quality control. Policy support for the development of local manufacturing can help overcome import-dependence and the instability in prices. Finally, public procurement and design frameworks should make explicit alignment of the use of admixture with the reduction of embedded carbon and lower lifecycle costs to be an intersection of economic and sustainability goals.

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