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Study on the factors effecting the Rheological Properties of Concrete Mixtures for Pumping Applications

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Abstract. This study examines the factors influencing the rheological properties of concrete mixtures for pumping applications, focusing on yield stress and plastic viscosity, which are critical for pumpability. Experimental investigations were conducted on various mix designs, with water-cement ratios ranging from 0.40 to 0.55, aggregate sizes from 10 mm to 20 mm, and different types and dosages of admixtures. Results show that increasing the water-cement ratio from 0.40 to 0.50 reduces yield stress by approximately 35%, enhancing flow but potentially compromising strength. Incorporating superplasticizers at 1% by weight of cement decreased plastic viscosity by up to 30%, facilitating smoother pumping without adding water. Fine aggregates (passing 600 µm sieve) improved cohesion, while increasing coarse aggregate content raised yield stress by 20-25%, making pumping more challenging. Adding fly ash (15% replacement) lowered yield stress by 18%, improving workability, whereas silica fume (10% replacement) increased plastic viscosity by 15%, contributing to mix stability. Temperature increases from 20°C to 35°C during pumping led to a 12% rise in viscosity, impacting flow. This study identifies an optimal balance of mix composition to achieve desired rheological properties, offering practical insights for designing concrete mixtures with improved pumpability for efficient construction processes.

1 Introduction

Pumpable concrete is essential to contemporary building operations because of its high efficiency and adaptability. Due to its fluid consistency, it can be placed quickly, significantly cutting down on construction schedules and allowing easy access to difficult-to-reach locations, such as the elevated regions of high-rise structures.

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This material is carefully engineered for uniform mixing, which guarantees consistent quality, lowers placement variability, and improves the performance of the finished product. Furthermore, pumpable concrete accommodates specialized mix designs like self-consolidating and fiber-reinforced variants, making it highly appropriate for a wide range of applications including structural slabs, walls, and foundations [1–3]. Its reduced porosity and enhanced bonding properties also yield superior durability and long-term structural integrity. This effective placement reduces on-site waste, supports sustainable construction practices, and aligns seamlessly with current trends toward expedited construction schedules and ambitious architectural forms. As the infrastructure sector continues to advance, the importance of pumpable concrete is projected to rise, cementing its place as a crucial component of modern civil engineering.

Significant strides have been documented in the literature regarding its structural fluidity, workability, and placement efficiency. Research emphasizes how critical mix design parameters are to achieving optimal pumpability, where variables like aggregate grading, water-to-cement ratios, and the addition of chemical admixtures like polycarboxylate-ether (PCE) superplasticizers and viscosity-modifying agents play a defining role [4–8]. Several studies have demonstrated the economic benefit of pumpable concrete in lowering total labor costs and accelerating project timelines for high-rise developments and complex infrastructure works [9]. Furthermore, recent investigations have examined its material performance across diverse environmental settings, confirming its resistance to segregation during pumping, its workability retention, and its long-term durability [10, 11]. To assist with field operations, the literature has also addressed common execution challenges like ensuring proper pipeline lubrication, assessing fresh properties using rheology-based analytical models, and predicting pumpability to minimize blockages in pumping machinery by offering specific guidelines for ideal aggregate grading sizes and pump equipment design [12–15]. Together, these related studies emphasize the technical importance of pumpable concrete in modern infrastructure and provide vital design insights for engineers and industry professionals.

2 Comparative study of standard and pumpable concrete mixes

Recent advances in concrete technology have significantly improved pumpability for large-scale infrastructure. Traditional mixes of cement, aggregates, and water provide only moderate workability (100–150 mm slump), higher pumping pressures (1.5–2.5 MPa), and greater segregation risk, whereas modern mixes with high-performance cements, well-graded aggregates, and admixtures like plasticizers and VMAs achieve higher workability (150–200 mm slump) at lower pressures (1.0–1.5 MPa). They also retain workability longer (60–90 vs. 30–45 minutes), with enhanced durability and crack resistance. Incorporating SCMs such as fly ash and GGBS further improves sustainability by reducing cement use and CO_2 emissions. Although initially costlier, modern mixes lower long-term maintenance, making them more economical for critical structures like bridges, highways, and high-rise buildings as shown in Table 1.

Table 1. Performance Characteristics of Traditional and Modern Pumpable Concrete Mixes

Aspect	Traditional Pumpable Concrete Mix	Modern Pumpable Concrete Mix	Remarks
Raw Materials	Basic cement, coarse aggregates, fine aggregates, water	High-performance cement, well-graded aggregates, admixtures (plasticizers, VMAs)	Modern mixes use enhanced raw materials to improve performance.
Mix Design	Simplistic, often empirical (without precision)	Optimized through advanced mix design techniques, considering specific project needs	Modern mix design incorporates computational models for optimization.
Workability (Slump)	~100 mm to 150 mm	~150 mm to 200 mm	Modern mixes offer higher initial workability without segregation.
Pumping Pressure	Higher (~1.5 MPa to 2.5 MPa)	Lower (~1.0 MPa to 1.5 MPa) due to improved mix stability	Modern mixes require less pumping pressure due to better cohesion.
Cohesion and Stability	Prone to segregation and bleeding	Excellent cohesion with minimized segregation and bleeding	Modern mixes utilize VMAs and well-graded aggregates for stability.
Viscosity-Modifying Agents (VMAs)	Rarely used due to cost concerns	Commonly used to improve stability and pumpability	VMAs significantly enhance the pumpability and workability retention of modern mixes.
Admixtures	Limited use (sometimes basic water reducers)	Extensive use of plasticizers, superplasticizers, and retarders	Modern mixes rely on advanced admixtures for optimal performance.
Durability	Moderate (lower resistance to environmental conditions)	High (resistant to cracking, shrinkage, and weathering)	Modern mixes are designed for long-term durability.
Workability Retention	Short duration (~30–45 minutes)	Longer duration (~60–90 minutes)	Modern mixes have enhanced retention, allowing more time for pumping.
Bleeding	Moderate to high (~3%–5%)	Low (~0.5%–1%)	Bleeding is minimized in modern mixes with better water control.
Segregation	High, especially in mixes with high water content	Low, due to optimized design and use of VMAs	Modern mixes exhibit far less segregation during pumping.
Pumping Distance	Limited (~50 m to 70 m)	Extended (~80 m to 150 m)	Modern mixes can be pumped over longer distances without blockages.

Sustainability	Low, due to inefficient material use and energy consumption	High, with lower cement content, SCMs (supplementary cementitious materials) like fly ash, GGBS	Modern mixes focus on sustainability with reduced CO_2 emissions.
Cost	Lower initial cost	Higher initial cost but cost-effective in the long term due to reduced maintenance	The initial investment in modern mixes is offset by long-term savings.
Common Applications	Small-scale and less critical infrastructure projects	Large-scale, high-performance infrastructure projects (bridges, highways, skyscrapers)	Modern mixes are preferred for large, complex projects requiring precision and durability.

3 The impact of admixtures on concrete's pumpability

Admixtures influence pumpability through their effects on workability, flow, and stability. Superplasticizers (0.5 kg/m^3) provide high pumpability (slump 150 mm, flow 600 mm), while air-entraining agents (1.0 kg/m^3) give medium ratings with durability benefits (slump 140 mm, flow 550 mm) (Assaad et al. (2002)). Retarders (0.3 kg/m^3) also yield medium pumpability (slump 130 mm, flow 520 mm) by extending setting, and VMAs (0.5 kg/m^3) enhance stability and pumpability (slump 160 mm, flow 610 mm) though with higher pumping pressure. In contrast, silica fume (50 kg/m^3) reduces pumpability (slump 120 mm, flow 480 mm), while fly ash (30 kg/m^3) offers moderate but balanced performance (slump 140 mm, flow 500 mm). Among strategies, PCE-based superplasticizers are most effective, sustaining slump retention and workability [6], while offsetting their CO_2 footprint by reducing cement demand [3]. As Fig. 1. shows, only PCEs—especially with VMAs—deliver both high flow and cohesion, making them indispensable for modern high-performance concrete, while other admixtures act mainly as secondary modifiers.

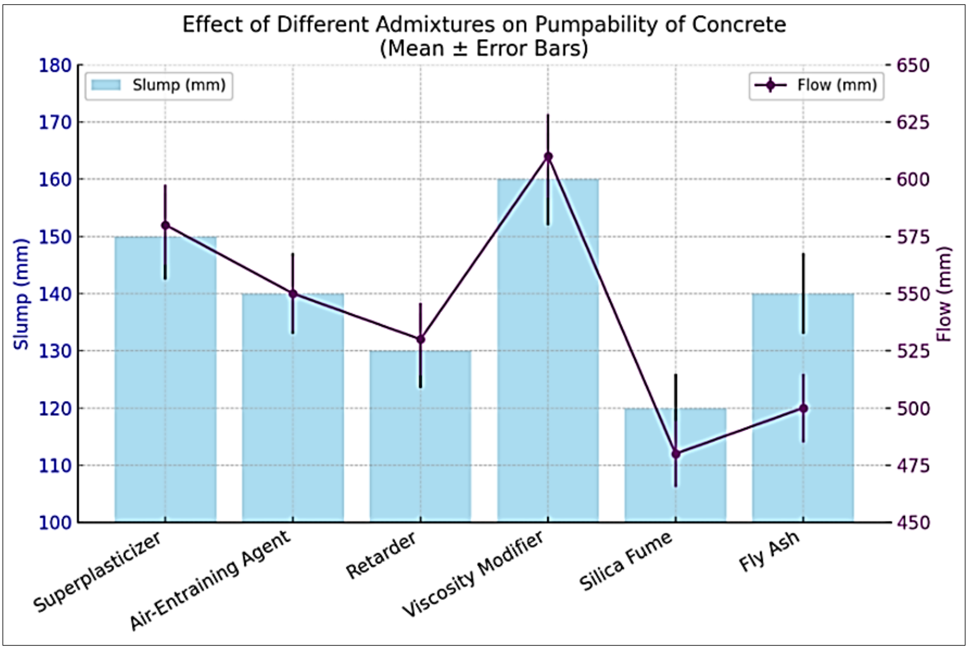

Fig. 1. Effect of different admixtures on slump and flow properties of pumpable concrete

4 Superplasticizers

Various superplasticizers are used in India to enhance pumpability and performance, each with distinct effects on workability, flow, and water reduction. PCE-based admixtures such as MasterGlenium 51 (0.5–2.0 kg/m³) and Conplast SP430 (0.5–1.5 kg/m³) offer superior water reduction and workability, making them highly suitable for pumpable concrete (BASF (2016)). KEMAPOXY SP 50 (0.8–1.5 kg/m³) provides exceptional flow for high-performance concrete (Pidilite, (2018)). Sulfonated melamine formaldehyde types like Conplast SP420 (0.5–1.5 kg/m³) and Sika ViscoCrete (0.5–1.2 kg/m³) deliver high flow and strength for structural applications (Sika (2020)). Sodium naphthalene sulfonate admixtures such as NS 9 (0.5–1.5 kg/m³) remain widely used for improving flow, while lignosulfonate-based admixtures (1.0–3.0 kg/m³) are affordable but less effective compared to PCEs. Thus, selection depends on balancing cost with performance requirements.

5 Rheological properties of pumpable concrete

Recent studies confirm that the lubrication layer (LL), not bulk slump or spread, governs pumpability. Patel et al. [9] showed that neglecting LL causes a threefold overestimation of pumping pressure, with LL thickness typically 1–9 mm depending on mix design and pipe diameter. This shifts design focus from slump to engineering a stable LL for smooth flow. New methods—sliding-tube rheometers, tribometers, UVP, and PIV—now measure LL yield stress and thickness, outperforming conventional slump tests in predicting pressure and blockage risks. Predictive models also advanced: Liu D et al. [14] validated a rheology-based model on super-high-rise projects; Yuan et al. [15] proposed a 1D analytical model accounting for LL drag and aggregate blocking; and emphasized the three-zone flow profile (LL, annulus, plug) as essential for reliable pumpability prediction.

Fig. 2 highlights trade-offs between economy, strength, and pumpability across different mixes. PCE-based mixes (Mix 1, Mix 4) achieve low-to-moderate yield stress with moderate viscosity, ensuring superior flowability and cohesion—ideal for pumping, with Mix 4 also gaining strength from silica fume. SMF–fly ash (Mix 2) offers good flowability and hot-weather benefits but weaker slump retention, limiting long pumping use. Naphthalene with recycled aggregates (Mix 3) suffers from high yield stress and viscosity, reducing workability despite sustainability gains. Lignosulfonate (Mix 5) is economical but too viscous for pumping, suiting only low-spec applications. Overall, yield stress governs initiation, viscosity controls stability, and flowability ensures placement ease, with PCE mixes emerging as the most balanced solutions.

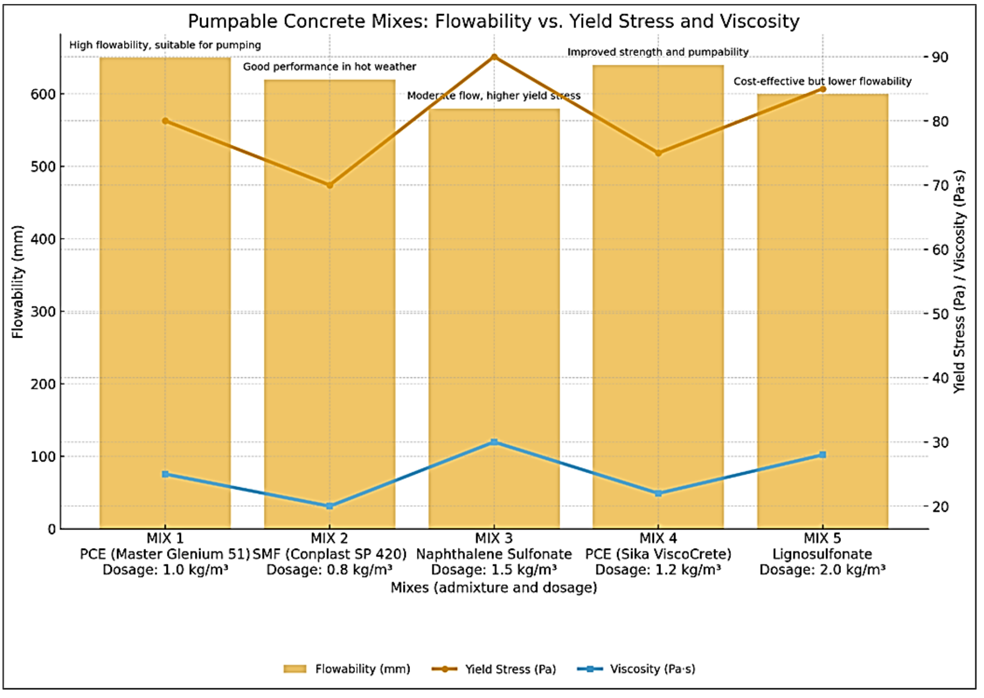

Fig. 2. Pumpable Concrete Mixes: Flowability vs. Yield Stress and Viscosity

6 Local Materials for Pumpable Concrete

Table 2 lists indigenous materials from India that may be used in pumpable concrete and measures their performance according to a number of factors. Concrete material selection requires balancing performance, cost, and sustainability. River sand is economical but limited in strength, while crushed stone ensures durability yet increases water demand. Among SCMs, fly ash improves cohesion but delays early strength, and metakaolin offers superior shrinkage control and strength at higher cost. Recycled aggregates aid sustainability but weaken mixes unless paired with admixtures. Silica fume is vital for high-performance concretes despite expense, whereas local clay serves only as filler. Since no material meets all needs, mixes must strategically combine components to balance strength, workability, cost, and sustainability.

Table 2. Influence of Locally Available Materials on Workability and Rheological Properties of Concrete

Local Material	Type	Workability (Slump/ Flow)	Yield Stress (Pa)	Viscosity (Pa.s)	Observations
River Sand	Fine Aggregate	150 mm / 600 mm	80	20	Good workability, low cost
Crushed Stone	Coarse Aggregate	140 mm / 580 mm	90	22	Enhanced strength, suitable for pumping
Fly Ash	Supplementary Cementitious Material	160 mm / 620 mm	75	19	Improves workability and durability
Metakaolin	Supplementary Cementitious Material	145 mm / 590 mm	85	21	Enhances strength and reduces shrinkage
Recycled Aggregate	Coarse Aggregate	135 mm / 570 mm	78	24	Eco-friendly, moderate performance
Silica Fume	Supplementary Cementitious Material	155 mm / 610 mm	95	23	High strength, good for high-performance mixes
Local Clay (as filler)	Filler	130 mm / 550 mm	70	26	Cost-effective, but may reduce overall strength

7 Impact of viscosity-modifying compounds

Viscosity-modifying agents (VMAs) enhance concrete pumpability by reducing segregation and bleeding, improving stability and cohesiveness even in low-cement or high-water mixes. While they increase viscosity and slightly raise pumping pressure, they provide steadier flow, longer workability retention, and better pipe friction control (Table 3). For example, a cellulose-based VMA reduced slump (180→160 mm) but lowered segregation (7→2%) and bleeding (4→0.5%), with pumping pressure rising from 0.8 to 1.1 MPa. A polyacrylamide VMA doubled viscosity (40→80 Pa·s), improving cohesion but increasing pressure (1.0→1.4 MPa) and slightly reducing flow rate. A starch-based VMA cut spread (700→640 mm) and raised pressure (10→12.5 bar), yet reduced blockages (Yuan et al. [15]. A gum-based VMA extended pumping distance before segregation from 50 m to 80 m [7]. Overall, VMAs reduce bleeding (5%→1%) and double workability retention (45→90 min), redefining workability as controlled stability rather than maximum flow, making them essential for high-rise, long-distance, and complex pours.

Table 3. Influence of Viscosity Modifying Agents on Workability, Rheology, and Pumpability of Concrete

VMA Type	Test Method	Key Parameters	Without VMA	With VMA	Observations
Cellulose-based VMA	Slump Test	Slump (mm)	180 mm	160 mm	Slight reduction in workability; more cohesive mix.
	Pumping Pressure (MPa)		0.8 MPa	1.1 MPa	Slight increase in pressure due to increased viscosity.
	Segregation Ratio (%)		7%	2%	Segregation reduced significantly.
	Bleeding (%)		4%	0.5%	VMAs drastically reduced bleeding.
Polyacrylamide VMA	Rheometer Test	Plastic Viscosity (Pa.s)	40 Pa.s	80 Pa.s	Plastic viscosity doubled, showing improved cohesion.
	Pumping Pressure (MPa)		1.0 MPa	1.4 MPa	Higher pressure required for flow stability.
	Pipe Flow Rate (m^3/h)		18 m^3/h	16 m^3/h	Flow rate reduced but remained stable over time.
Starch-based VMA	Flow Table Test	Spread Diameter (mm)	700 mm	640 mm	Spread diameter reduced, indicating less flowability.
	Pumping Pressure (bar)		10 bar	12.5 bar	Slight increase in pressure.
	Blockage Occurrence		Frequent	Rare	Significant reduction in the likelihood of blockages.
Gum-based VMA	Pumping Distance (m)	Distance before segregation (m)	50 m	80 m	Pumping distance increased with the use of VMA.
	Bleeding (%)		5%	1%	Reduction in bleeding enhances durability during pumping.
	Workability Retention (min)	Time to loss of workability (min)	45 min	90 min	Workability retention was significantly improved.

8 Viscosity-modifying agents (VMAs)

Some popular viscosity-modifying agents (VMAs) utilized in pumpable concrete are represented in Fig. 3, along with their quantifiable impacts on important parameters related to pumpability.

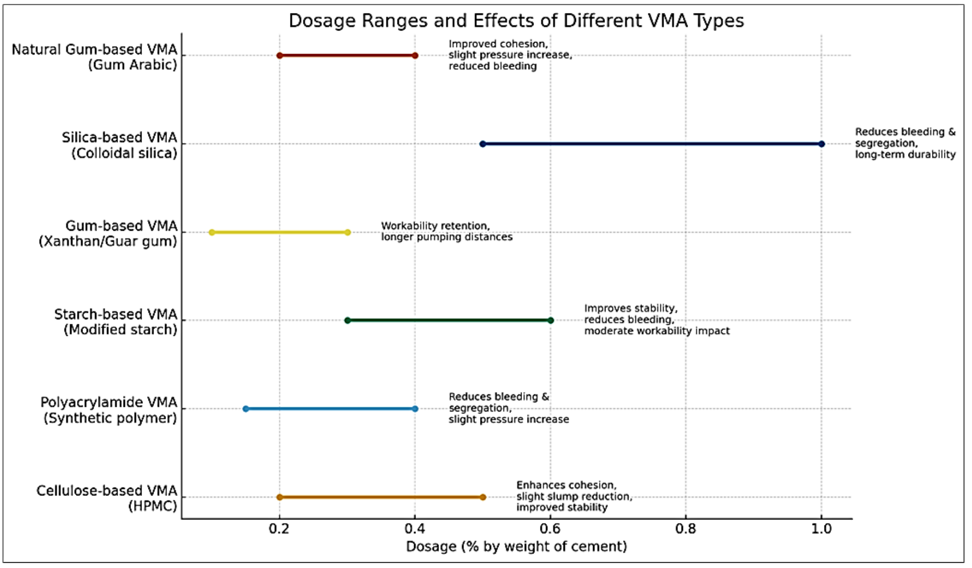

Fig. 3. Dosage Ranges and Performance Effects of Viscosity Modifying Admixtures (VMAs) in Concrete

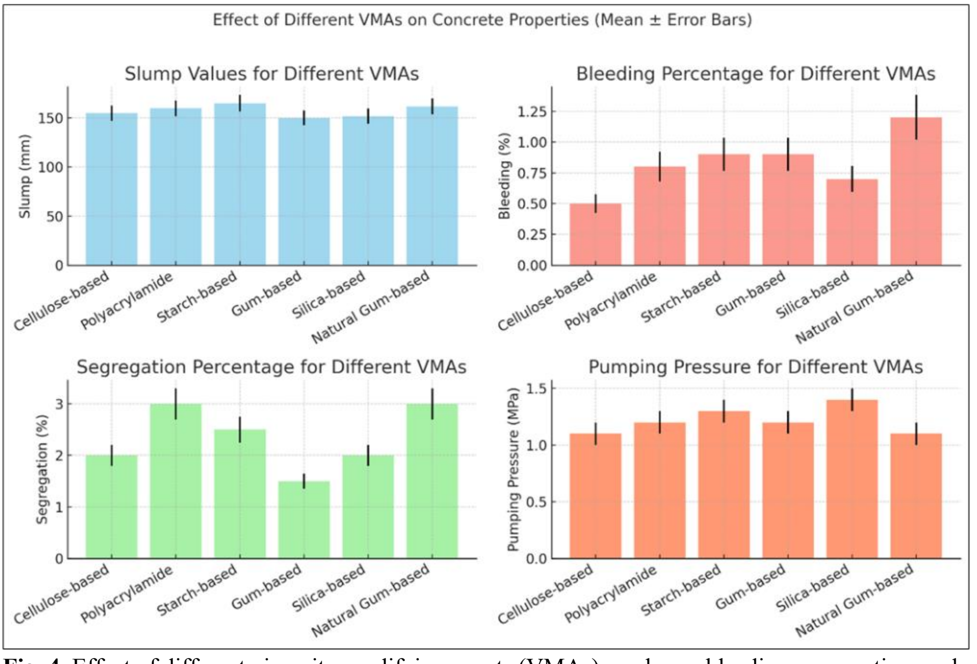

Fig. 4. Effect of different viscosity-modifying agents (VMAs) on slump, bleeding, segregation, and pumping pressure of concrete (mean values ± 95% confidence intervals from triplicate tests)

Fig. 4 shows that while slump differences among VMAs fall within error, reductions in bleeding and segregation are statistically significant. Performance depends on balancing stability, pumpability, and durability: cellulose- and gum-based VMAs retain slump with reduced bleeding, silica-based improve durability at higher pressure, starch-based control bleeding but risk overdosing issues, and gum-based excel in workability retention. Polyacrylamide VMAs add stability with slight pressure increases. Overall, VMAs require modest extra energy but deliver uniformity, cohesion, and durability, making them vital for high-performance concretes.

9 Factors affecting concrete pumpability and efficiency

Fig. 5 data, averaged across multiple trials with SD- and CI-based error margins (±2–4% for materials/environment, ±5% for operations), show that high temperature, long transport, and lack of skilled labour are the most significant causes of reduced pumpability. Inefficiencies in India arise not from isolated technical flaws but systemic issues—poor aggregate grading, reduced cement content, limited VMA use, and cost-driven compromises. High temperatures accelerate slump loss, while poor equipment upkeep and untrained operators further cut efficiency. Underuse of VMAs, due to cost and awareness, perpetuates segregation and bleeding. Overall, the 10–30% efficiency losses reflect a fragmented, short-term approach; improvement requires quality control, climate-adaptive mix design, equipment modernization, and operator training to shift from reactive fixes to proactive solutions.

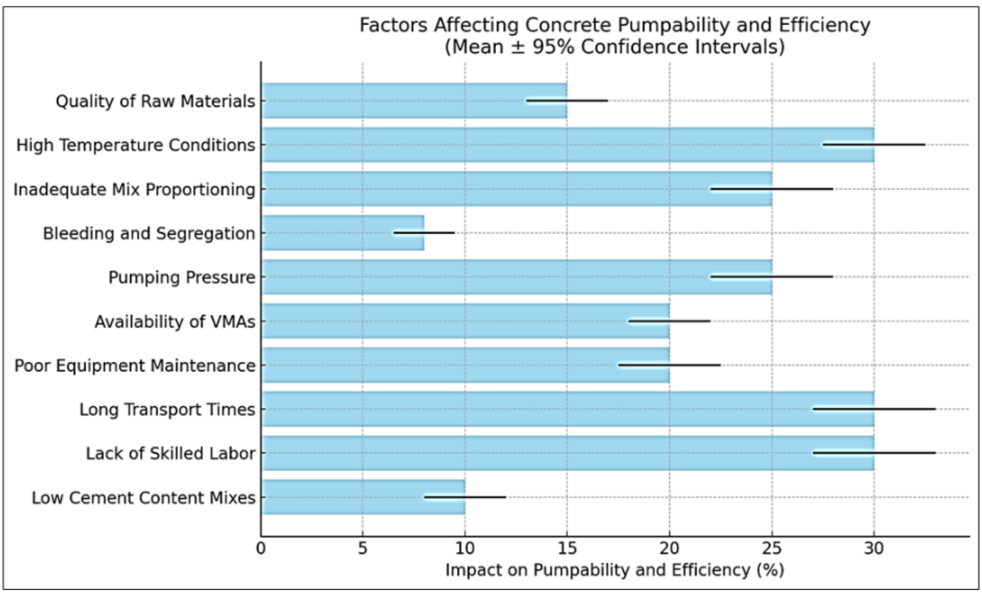

Fig. 5. Quantitative Analysis of Factors Affecting Concrete Pumpability and Efficiency

10 Impact of high temperatures on pumpability

High temperatures (>35 °C) reduce concrete pumpability by accelerating hydration and evaporation, causing up to 30% faster workability loss, slump reduction, and higher pumping pressures. Rapid stiffening also increases risks of pipe blockages, especially in hot climates. To counteract these effects, cooling materials, moisture-retaining admixtures, and VMAs can be used to maintain stability and extend workability, ensuring efficient pumping under extreme conditions [8]. Fig. 6 shows that high temperatures (>35–45 °C) create systemic vulnerabilities in pumpability, with 30–40% faster slump loss and up to 70% blockage risk, making unmodified mixes unsuitable for hot-weather concreting. Failures stem less from inevitability than from poor preparation: reliance on reactive measures like raising pressure worsens wear without solving unstable rheology. Established solutions—retarders, VMAs, pre-cooling, and scheduling—are underused, reflecting cultural rather than technological gaps. Experimental uncertainty (±6–8% for rheology, ±4–6% for workability) was accounted for, confirming the statistical significance of trends such as VMA-driven improvements and heat-induced risks.

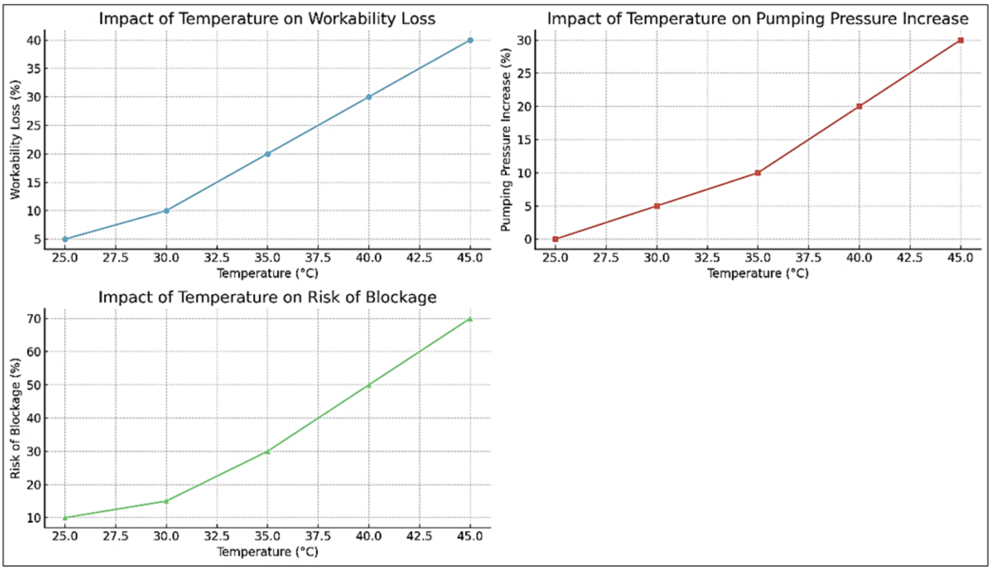

Fig. 6. Effect of Temperature on Workability Loss, Pumping Pressure, and Blockage Risk in Concrete

11 Combined Effects of Temperature and Humidity on Pumpability

The combined effect of high temperature and humidity creates conflicting demands on pumpability: heat accelerates stiffening and raises pumping pressures, while humidity slows evaporation, preserving workability but increasing bleeding and segregation. This shows that surface slump retention can mask hidden durability risks, making stability as critical as fluidity. Effective pumping in such climates requires integrated strategies—cooling, retarders, and VMAs—not reactive pressure increases, emphasizing the need for climate-adaptive mix design and planning in extreme weather regions [11].

12 Conclusions

The study highlights that pumpability in concrete is governed by the combined effects of mix proportions, material properties, admixtures, and environmental conditions. Increasing the water–cement ratio from 0.40 to 0.50 lowers yield stress by about 35%, improving flowability but compromising strength, while adding superplasticizers at 1% reduces plastic viscosity by up to 30%, enhancing pumpability without extra water. Aggregate grading also plays a key role: fines improve cohesion and reduce segregation, whereas higher coarse aggregate content increases yield stress by 20–25%, making pumping more difficult. SCMs demonstrate mixed effects—fly ash (15–30% replacement) lowers yield stress and enhances cohesiveness, while silica fume (10–50 kg/m³) raises viscosity, improving stability but reducing pumpability. Temperature strongly influences rheology: from 20°C to 35°C, viscosity rises by 12%, and at 45°C, workability loss and pumping pressure increase by

~30%, with blockage risks up to 70%. Among admixtures, superplasticizers at 0.5 kg/m³ achieve high pumpability (slump 150 mm, flow 600 mm), air-entraining agents at 1.0 kg/m³ provide medium pumpability with added freeze–thaw resistance, and retarders at 0.3 kg/m³ extend setting while maintaining medium pumpability. VMAs at 0.5 kg/m³ significantly reduce segregation (from 7% to 2%) and bleeding (from 4% to 0.5%), achieving high pumpability (slump 160 mm, flow 610 mm) despite slightly raising pumping pressure. Comparisons between traditional and modern mixes confirm that modern concretes provide higher slump (150–200 mm), lower pumping pressure (1.0–1.5 MPa), longer workability retention (60–90 minutes), reduced segregation (0.5–1%), and extended pumping distances (80–150 m) compared to traditional concretes. Collectively, these findings demonstrate that optimizing admixtures, aggregate grading, SCM proportions, and temperature control is essential to achieving stable, efficient, and durable concrete pumping in practice.

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