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Developing a quality index for pavement construction and rehabilitation

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Abstract: Keeping in view the severe lack of research in the field of quantification of pavement quality, an analysis of suitable methods for quantifying the quality of pavement construction and rehabilitation was carried out in this study. The main and sub-factors that significantly impact the quality of pavement construction and rehabilitation from managerial and constructional perspectives were identified using a questionnaire survey. A pavement construction and rehabilitation quality index equation has been developed that yields a quantified level of quality achieved in a project in terms of percentage. Ranking analysis of the top six influencing main factors revealed that constructional factors, such as paving and compaction practices and subsurface drainage, are more important than managerial factors, such as the client's and quality consultant's capability, payment and finances, and contractor's capability. Sensitivity analysis revealed that each sub-factor has its individual significance on the overall quality index, irrespective of the rank of its main factor, and the quality index equation developed in this study duly encompasses the impact of each sub-factor and main factor, collectively, on the overall quality index. The practical application of the developed index was also validated through a case study. This study is one of the pioneer studies that specifically explored the quantification of pavement rehabilitation and construction quality in terms of a quality index, duly encompassing both managerial and constructional aspects. The results of this study and recommendations for future research can be effectively used as a benchmark checklist to improve particular

main and sub-factors in order to enhance the overall quality of pavement rehabilitation and construction in future projects.

Keywords: pavement evaluation, pavement quality, quality assessment, quality control, quality index, quality quantification, road resurfacing quality

1 Introduction

This study addresses the existing gap in research on the quantification of pavement construction and rehabilitation quality. The study identifies and quantifies the main factors and sub-factors. The weights assigned also act as a baseline check for the prioritisation of factors while performing pavement construction and rehabilitation works. Using quantified factors, a quality index was developed that acts as a tool to quantify the quality in the form of a numeric value.

Quality, safety and environment have an integrated impact on risk management, and strategies are required to be managed differently (Zeng et al. 2010). Managing quality, safety and environment collectively results in successful project management (Ershadi et al. 2020). The integrated and organised management of these traditionally independent aspects results in efficient and effective performance of organisation (Hamid et al. 2004; Griffith 2018). There is a lack of research and strategies that consider an integrated approach for quality, safety and environment management and prioritise their role in the success of projects in the public road sector (Mahamadu et al. 2015). Although this study relates solely to the quality management aspect of pavement construction and rehabilitation, it will act as an initial step towards the integrated approach for quality, safety and environment management.

With road construction on the rise globally, ensuring the quality and longevity of pavement infrastructure has become increasingly imperative. Pavements are a major

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part of infrastructure that facilitates multiple modes of transportation and are considered highly valuable assets of governments around the world (Saeed 2013). The significant importance of pavements and their increasing lengths are the reasons why their quality needs to be focused on. Changes in temperature and overloading throughout the year result in rutting, disintegration and development of stresses in the road network (Khan and Asghar 2013). With the passage of time, the number and length of roads have been increasing globally, leading to an increased requirement of quality maintenance and rehabilitation of precious highway assets (Rahaman et al. 2020).

Pavement rehabilitation faces several quality-related issues. The absence of a well-developed quality assessment methodology is likely to yield low-quality pavement rehabilitation and construction, leading to premature deterioration and failure of pavements, especially in developing countries (Chang et al. 2016; Lu et al. 2018). Though pavement performance and quality greatly hinge on achieving the desired material properties and test standards in the construction phase, adherence to appropriate construction and rehabilitation practices and effective quality management also play a vital role in ensuring the desired quality of pavements. Considerable research has been carried out to explore the material properties affecting pavement performance (Hasan and Sobhan 2020; Zumrawi 2021).

The quality control practices followed in hot-mixed asphalt (HMA) pavements need significant improvements because they are not efficiently serving the desired purpose (Horan et al. 2012). Usually, quality-related challenges are a result of poor-quality management during the construction of HMA pavements; therefore, proper supervision is mandatory to achieve high-quality results (Olutaiwo and Adanikin 2020). Strict adherence to proper pavement maintenance and rehabilitation practices is mandatory to ensure high quality and longevity of pavements (Speller 2019).

Leadership plays a pivotal role in the performance of construction projects. Project managers should constantly manage and monitor the construction activities for construction projects to serve their lives efficiently. Proper leadership, along with strong financial management, is an important attribute that results in good quality projects. Compromising on quality significantly reduces the lifespan of infrastructure; consequently, more resources are required to be allocated for maintenance, which affects socio-economic growth (Dixit 2020; Yap et al. 2022). The importance of managers and supervisors in ensuring construction quality should not be overlooked. Along with a task-oriented approach, managers should motivate other

stakeholders to understand the significance of quality in construction (Zhao et al. 2016). Based on a study reviewing four decades of prior research, leadership's approach was one of the major factors that needs attention for the quality of construction projects (Ofori 2015). The project manager is primarily responsible for ensuring quality control and assurance implementation, while the construction manager is responsible for the coordination of measures and constructional practices in the field. Therefore, the leadership's role in the implementation of a well-established and efficient quality management system is imperative (Bhattacharjee 2018; Muhumed 2022).

Governments, in coordination with the leadership of companies, should devise strategies to mentor contractors so that any quality-related issues in road construction projects can be identified at an early stage. Most countries consider the poor performance of contractors to be the most important reason for quality-related challenges faced in road construction projects (Mashwama et al. 2018). Therefore, there is a dire need to devise quality management tools and innovative strategies to achieve high-quality roads that last longer. The implementation of the devised tools and strategies must be made mandatory at the leadership and governmental levels, as it has a direct relation with the economic development of a country.

The review of literature reveals that factors affecting the quality of pavement rehabilitation, in particular, and pavement construction in general have not been explored well, especially from a constructional perspective. A few studies have highlighted the factors related to the quality of pavement construction from a managerial perspective, but there is a considerable lack of research on the factors affecting the quality of pavement rehabilitation from a constructional perspective. Therefore, there is a dire need to analyse the factors affecting the quality of pavement rehabilitation from constructional and managerial perspectives.

With this background, an analysis of suitable methods for quantifying the quality of pavement construction and rehabilitation was carried out in this research. Using a questionnaire survey, a ranking analysis of important factors that significantly affect the quality of pavement construction and rehabilitation from managerial and constructional perspectives was carried out. A quality index equation has been developed in this study to rate the quality of pavement rehabilitation and construction. A case study and sensitivity analysis also constitute an important part of this research, which explored the influence of important factors on the quality of pavement rehabilitation and construction.

2 Literature survey

A rigorous review of the past literature revealed that there is a considerable lack of research on factors affecting the quality of pavement rehabilitation and the quantification of pavement construction and rehabilitation quality. Factors affecting the quality of construction in general and pavement construction in particular have been explored with a managerial perspective, but very few studies have focused on these aspects from a constructional perspective.

According to a study conducted in India, the uncertainties in quality levels of construction for pavement rehabilitation are inherent. The study suggested that good quality control and its assurance result in a longer life of the pavements (Das and Siddagangaiah 2022). Improper quality management procedures result in early degradation of pavements. Proper planning, availability of adequate funds, good quality of materials, presence of skilled inspectors, labour and trained managerial staff, along with better machinery, must be adopted for effective maintenance of roads (Rani and Hussain 2021).

A Semarang, Indonesia-based study showed that poor drainage and low-quality materials are two major causes of the rapid deterioration of pavements. The results demonstrated that pavement maintenance and rehabilitation works were ineffective and led to poor quality of roads (Gnefeda et al. 2021). A Sudan-based study established that a lack of good quality construction materials, poor drainage systems and improper construction practices were some of the major causes of poor construction quality of pavements (Zumrawi 2021). Nyakala et al. (2019) revealed that very little importance has been given to sustained quality and quality management in road construction projects. Poor quality of road construction has been found to be one of the major reasons, which leads to premature failure before design life (Suryanarayana et al. 2021). Bazlamit et al. (2017) indicated that there is a lack of systematic strategy that could be followed to maintain the quality of rehabilitation and maintenance of pavements. The less focus of stakeholders, specifically leaders, on introducing new strategies in highway construction is another major cause that results in quality compromise in highway construction (Ogunrinde et al. 2021). In addition to that, stakeholders' engagement strategies need to be revisited. The government and contractors should play a pivotal role in engaging the primary and secondary stakeholders to mitigate the issues that result in quality compromise in construction projects (Ebekozen et al. 2024). To achieve success, stakeholder engagement strategies should be constantly reviewed for efficient construction management (Collinge 2020).

Advanced performance measurement, monitoring and evaluation tools must be devised to assist contractors and managers in the measurement of critical project objectives during the pavement construction phase and to address the quality-related issues in pavement construction projects (Nassar and AbouRizk 2014; Hussain et al. 2018).

A considerable number of studies have been found in the past literature that focused on numerous aspects that directly or indirectly influence pavement maintenance and rehabilitation quality, primarily from a managerial (non-constructional) perspective (Chen and Flintsch 2007; Haider and Dwaikat 2011; Moazami et al. 2011; Gao et al. 2012; Su 2013; Hajibabai et al. 2014; Elhadidy et al. 2015; Yepes et al. 2016; Imran et al. 2019). Table 1 shows the summary of some key factors affecting pavement construction quality found in the past literature.

After a thorough literature review, it was determined that quality practices being followed in pavement rehabilitation and construction are not well-developed, especially from a constructional practices perspective. There is still a significant gap in research regarding the assurance of quality for construction and rehabilitation of pavements. Most importantly, it was revealed that very few studies have specifically focused on the factors affecting the quality of pavement rehabilitation, in particular with a constructional practices perspective. Moreover, there is a considerable lack of research on the quantification of pavement construction and rehabilitation quality. Therefore, there is a dire need for a methodology that can address the gap in quality management in pavement rehabilitation and construction. There is a need to develop an index that helps to quantify the level of quality by duly considering constructional and managerial aspects. This study specifically addresses the highlighted gap in the research by exploring the quantification of pavement rehabilitation and construction quality, duly incorporating managerial and constructional perspectives simultaneously. The quality index developed in this study will help estimate the quality of pavement construction and rehabilitation as well as assign a numeric value to quality out of 100.

3 Research methodology

This section presents a brief summary of the overall research methodology that was followed in this study (Figure 1). A rigorous review of past research was carried out, focusing on aspects regarding pavement construction in general and pavement rehabilitation in particular;

Tab. 1: Summary of factors affecting pavement construction quality from the past literature.

Factors	References
Inspection team of client	Al-Hassan 1993; El-Maaty et al. 2016; Nyakala et al. 2019
Availability of quality consultant	Al-Hassan 1993; El-Maaty et al. 2016
Lowest bid	Abas et al. 2015; El-Maaty et al. 2016
Financial capability of contractors	Abas et al. 2015; El-Maaty et al. 2016; Yepes et al. 2016; Smith et al. 2016
Work subcontracted	Al-Hassan 1993; El-Maaty et al. 2016
Equipment with contractor	Wambui et al. 2015; Abas et al. 2015; El-Maaty et al. 2016
Escalation of costs	Abas et al. 2015; El-Maaty et al. 2016
Assigning clear responsibilities	Al-Hassan 1993; El-Maaty et al. 2016
Competent managers	Jha and Iyer 2006; Wambui et al. 2015
Availability of finances for project	Al-Hassan 1993; Abas et al. 2015; Wambui et al. 2015; El-Maaty et al. 2016; Yepes et al. 2016; Hasan and Sobhan 2020; Nyakala et al. 2019
Clarity in assignment of roles and responsibilities	Al-Hassan 1993; El-Maaty et al. 2016
Surface cleanliness	Long 2017; Mohammad et al. 2010; Yaacob et al. 2014
Crack repair	Long 2017; Gong et al. 2016; Lu et al. 2018; Speller 2019; Ayed et al. 2018
Milling methodology	Yaacob et al. 2014; West 2015; Lu et al. 2018; Speller 2019; Ayed et al. 2018
IRI	Gong et al. 2016; Chong et al. 2018; Gushgari et al. 2018
HMA temperature	López et al. 2019; Jahanian et al. 2017; Galić et al. 2017; Hayat et al. 2019
Compaction practices	Cantisani et al. 2016; Liu et al. 2018; Gao et al. 2018; Hayat et al. 2019; Roozbahany et al. 2013; West 2015
Maintaining design cross slope	West 2015
Maintenance of HMA temperature	Chu and Fwa 2020; Rahman et al. 2020; He et al. 2020
Poor drainage	Rani and Hussain 2021; Yepes et al. 2016; Zumrawi 2021; Hasan and Sobhan 2020
Organisational structure	Nyakala et al. 2019; Mwangi 2016; Karim and Magnusson 2008; Smith et al. 2016

HMA, hot mixed asphalt; IRI, international roughness index.

factors affecting quality; quantification of quality and establishment of quality index. An analysis of suitable methods for quantifying the quality of pavement construction and rehabilitation was carried out in this study. The first phase of this research identifies the main and sub-factors that significantly impact the quality of pavement construction and rehabilitation from managerial and constructional perspectives, using a deliberate questionnaire survey. Weights were assigned to each main and sub-factor based on the data collected through the questionnaire. In the second phase of the study, a pavement construction and rehabilitation quality index equation has been developed that yields a quantified level of quality achieved in a project (i.e. quality rating) in terms of percentage. The practical application of the developed index was also validated through a case study. Using the quality index, a sensitivity analysis was carried out to explore the influence of important main and sub-factors on the quality of pavement rehabilitation and construction from managerial and constructional perspectives.

4 Development of questionnaire and conduct of survey

Following a detailed synthesis of past literature on the subject and the expert opinion of experienced professionals, a list of all important main factors and their sub-factors affecting the quality of pavement construction and rehabilitation was prepared. Based on the established list of factors, a survey questionnaire was prepared. Thirty selected experienced and highly qualified professionals rendered their expert opinion during the pilot survey. The list of main factors and their sub-factors was refined based on this pilot survey, and the main survey questionnaire of this research was prepared based on 15 main factors and 131 sub-factors (Tables 2 and 3). The finalised survey questionnaire was responded to by 185 individuals from both academia and field/industry. The education and experience of selected respondents are shown in Figures 2 and 3.

Respondents were asked to rate the main factors and sub-factors, according to their knowledge and experience,

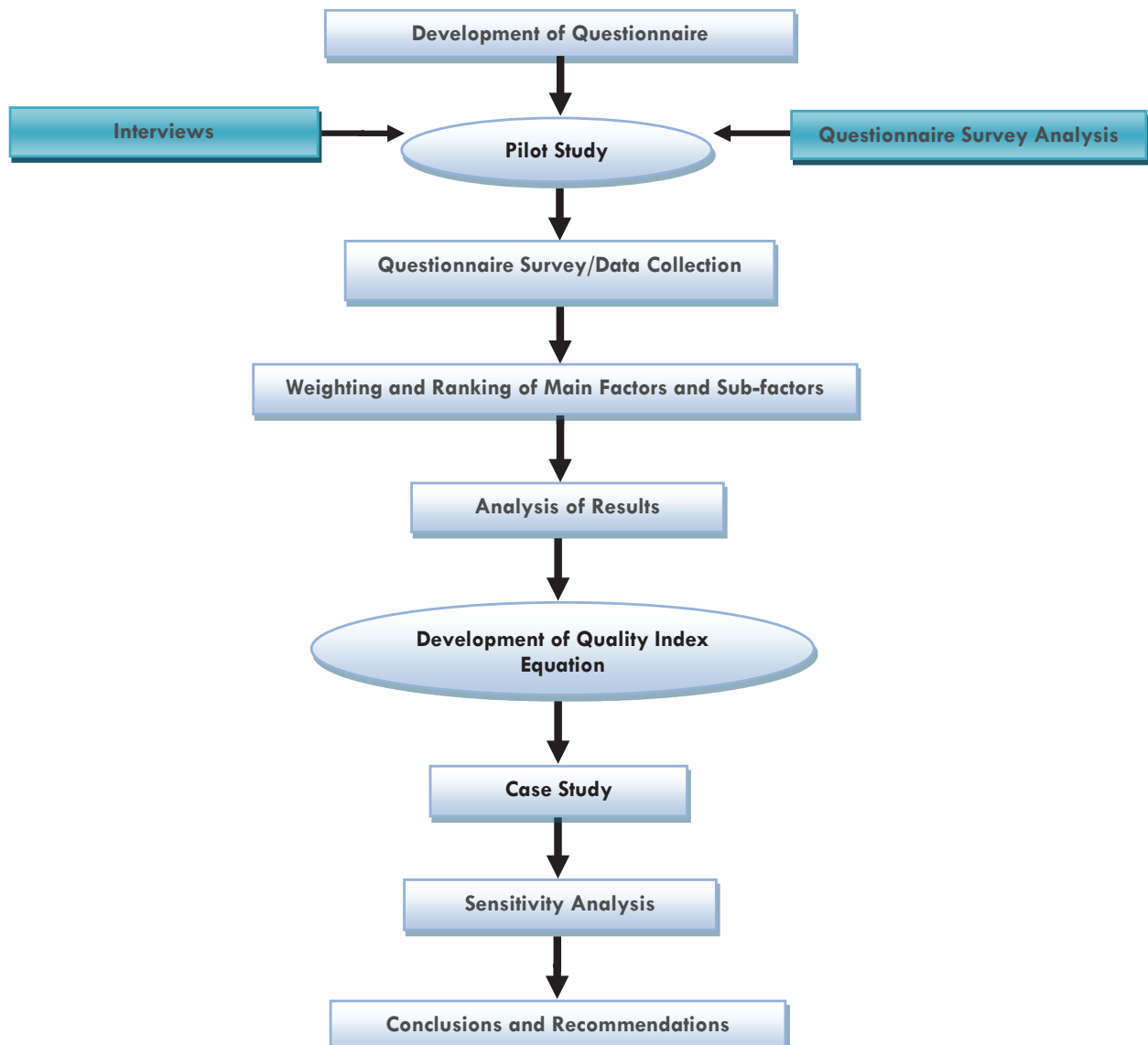


Fig. 1: Research methodology.

on a five-point Likert scale where: 1 – Irrelevant; 2 – Not so important; 3 – Important to some extent; 4 – Significant and 5 – Extremely important. The ratings given to each sub-factor and main factor by the respondents were used as a basis to assign weights to them and apply the weighted average method. The weights exhibit the significance of each factor and sub-factor. The factors and sub-factors were then ranked based on the aforementioned calculations.

After the assignment of the weights, a quality index equation was developed. An analogous application of weights and score has been observed in past research (Fetscherin and Stephano 2016; Song and Kang 2016; Imran et al. 2019). Internal consistency was evaluated using Cronbach's alpha coefficient, as it has been

extensively used for this purpose in past research (Deng and Chan 2017). The value for Cronbach's alpha was 0.934, which represents significant consistency. A description of the identified main factors and sub-factors affecting the quality of pavement rehabilitation from managerial and constructional perspectives is given in the ensuing section.

5 Factors affecting quality of pavement construction and rehabilitation

This section presents a description and ranking of the main factors and sub-factors, influencing the pavement

Tab. 2: Constructional practices related main factors and sub-factors affecting pavement construction and rehabilitation quality.

Main factors	Sub-factors	Weights for sub-factors	Rank (sub-factors)
Brooming and cleanliness	Cleanliness of milled surface from loose material, dust, drop-pings and residuals	0.2088	1
	Proper use of equipment	0.2068	2
	Dryness of the surface	0.2058	3
	Brooming before every prime/tack coat application	0.2004	4
	Use of hand brooms to remove the material leftover from the air compressor	0.1782	5
Compaction practices	Achieving 97%–98% of laboratory compaction/material density	0.0619	1
	Uniform/slow speed of the tandem rollers/PTR	0.0606	2
	Lubricating of PTR wheels with release agent	0.0601	3
	After compaction checking of pavement smoothness with a straight edge	0.0595	4
	Moisturising of roller wheels to prevent adhesion	0.0594	5
	Minimising of transverse joint	0.0589	6
	Overlapping of successive trips	0.0589	6
	Recommended air pressure in pneumatic tires of the paver group	0.0589	6
	Adherence to initial and breakdown rolling temperature	0.0587	7
	Adherence to pattern/sequence of compaction	0.0587	7
	Finish rolling to remove roller marks before cession temperature	0.0588	7
	Secondary or intermediate rolling with PTR	0.0586	8
	Requisite contact pressure for compaction	0.0581	9
	Continuous monitoring of time and duration of rolling	0.0571	10
	Avoidance of skin patching	0.0564	11
	Avoidance of backlash while using rollers in reverse direction	0.0556	12
Crack repair	Compaction of each lift	0.1065	1
	Milling of cracked area if cracks >(6–12) in 25–50 m area	0.1042	2
	Cutting/grooving method (asphalt cutter, small machine or jack hammer)	0.1034	3
	Tack coat application	0.1034	3
	Maximum lift thickness should not be more than 4 inches	0.1005	4
	Filling up the cracks with paver if they are in abundance	0.0987	5
	Sealing of minor cracks/patch edges	0.0984	6
	¼ extension of the final uncompacted lift above the surrounding pavement	0.0965	7
	Cleaning and drying of the grooved surface	0.095	8
	Chamfering of sharp edges	0.0934	9
Execution of joints	Cleanliness of dust	0.0881	1
	Application of tack coat on vertical face of cold joint	0.0867	2
	Matching of thickness, density and uniformity in two mats of hot joint	0.0856	3
	Cutting of edges by cutters	0.0848	4
	Meeting of the second overlay with previously placed pavement in depth, grade and slope in cold joints	0.0844	5
	Use of two pavers parallel in the hot joint	0.0834	6
	Cutting of longitudinal edge up to full depth in cold joints	0.0824	7

(Continued)

Tab. 2: Continued

Main factors	Sub-factors	Weights for sub-factors	Rank (sub-factors)
Fulfilment of road opening requirements	Cutting of longitudinal edge 75–100 mm from the joint	0.0818	8
	Absence of bump	0.0816	9
	Staggering of transverse joints of consecutive layers	0.0810	10
	Offsetting of longitudinal joint of lower layer from upper layer	0.0805	11
	Overlapping	0.0797	12
	IRI should be ≤ 1.5 m/km	0.1803	1
	Absence of longitudinal as well as transverse undulations	0.1702	2
	Minimum rest period of 24 h	0.1694	3
	Grinding of high spots, if any	0.1634	4
	Cooling of full depth of HMA to 40°C	0.1632	5
Milling methodology	Opening of freshly treated road at control speed for traffic	0.1535	6
	Efficiency of the milling machinery	0.1213	1
	Milling surface inspection to see the difference as compared to profile level	0.118	2
	Proficiency level of surveyor/operator	0.116	3
	Use of several sensors with milling machine, including grade sensors	0.1156	4
	Straightening of edges of adjacent unmilled pavement	0.11	5
	Depth of milling	0.1076	6
	Use of straight edge equipment	0.1065	7
	Speed of milling/drum	0.1062	8
	Disposal of milled material away from work zone	0.0988	9
Paving practices	Use of appropriate method for achieving design profile	0.0815	1
	Removal/dryness of rainwater, etc. prior to laying of HMA	0.0811	2
	Placing of HMA before heat loss	0.0807	3
	Setting of paver with appropriate compaction, cross slope and vibration	0.08001	4
	Spreading of mix according to established grade elevation and slope with paver	0.08001	4
	Setting of pavement screed for initial compaction and shape of the surface	0.0767	5
	Visual inspection of HMA	0.0767	5
	Bumping of paver to avoid production of hump	0.0763	6
	Consistency in layer thickness	0.076	7
	Use of automatic screed control	0.0757	8
Prime coat/tack coat application	Simultaneously laying of all lanes on one side of the median to avoid cold joints	0.07308	9
	Consistency of the head of material in front of the screed	0.073	10
	Keeping the hopper filled up with HMA all the time during the laying operation	0.0692	11
	Quality of material	0.0984	1
	Surface cleanliness/preparation	0.0968	2
	Uniform distribution of asphaltic liquid	0.0968	2
	Control/accuracy on rate of application	0.095	3

(Continued)

Tab. 2: Continued

Main factors	Sub-factors	Weights for sub-factors	Rank (sub-factors)
Sub-surface drainage system	Suitable rest or curing time (of 24 h) after the prime coat	0.093	4
	Requirement/application of tack coat on vertical faces of joints	0.0928	5
	Suitable method of application (hand pump/pressure distributor)	0.0892	6
	Proper curing of primed base	0.0887	7
	Non-tacky condition of prime coat before asphaltic operation	0.0867	8
	Application of next course within tackiness condition of tack coat	0.0865	9
	Spreading of sand, etc. to prevent picking up wheels of traffic	0.076	10
	Maintenance of design cross slope for surface runoff	0.1604	1
	Cleaning of the existing drainage system	0.1518	2
	Redressal of design faults/already existing faults	0.1492	3
Transportation of material within a suitable temperature	Drainage outlet ditches for protection works during construction	0.1406	4
	Drainage channel depth as same as milling depth	0.1351	5
	Cutting of temporary drainage channels in shoulders	0.1316	6
	Suitable spacing in between drainage channels/catch pits	0.1313	7
	Adherence to the requisite temperature of HMA while loading, unloading/laying and compaction	0.1339	1
	Avoidance of segregation and lumps	0.1317	2
	Visual inspection and test of asphalt mixture	0.129	3
	Bed of dumper should be free from debris or residual of previous supply	0.1275	4
	Compatibility of size paver vis-a-vis truck	0.1262	5
	Coating of truck bed with release agent	0.1187	6
	Allowing load to break before tailgate is opened	0.118	7
	Constant supply of HMA from plant to site	0.115	8

HMA, hot mixed asphalt; IRI, international roughness index; PTR, Pneumatic Tire Roller.

construction and rehabilitation quality, examined in this study from managerial and constructional perspectives. Each main factor has been explained in detail, highlighting its contribution to the overall quality of pavements, along with the association of each sub-factor with its main factor (Tables 2 and 3). The constructional perspective covers all steps and activities involved in pavement construction and rehabilitation, starting from the milling of pavement to the opening of the road for traffic operations. The managerial perspective encompasses the key construction management factors that affect the quality of pavement construction and rehabilitation, such as quality assurance/control system and financial management. Each main factor was then further analysed by considering important selected sub-factors that contribute to the influence of their main factor on the quality of pavement construction and rehabilitation.

5.1 Main and sub-factors affecting pavement quality from constructional practices perspective

Milling is carried out to remove old/damaged layers from the paved area. The quality of milling directly influences the quality of the new layer of pavement to be laid, as the surface beneath the removed material acts as a base for the new layer (Li et al. 2013). Milling removes the distressed layers, helps in the restoration of the roadway profile and cross slope and creates a strong bond with the overlay (West 2015). It provides the strength to generate the sufficient friction for shear force by traffic (Yaacob et al. 2014). Therefore, it is important to properly manage the milling operation. Key milling-related sub-factors that ensure quality resurfaced pavement include appropriately selecting the milling speed, depth

Tab. 3: Management related main factors and sub-factors affecting pavement construction and rehabilitation quality.

Main Factors	Sub-factors	Weights for sub-factors	Rank (sub-factors)
Client's and quality consultant's capability	Financial capability of the client	0.1564	1
	Keeping cyclic checks	0.1487	2
	Training of the consultant's team regarding pavement rehabilitation practices	0.1437	3
	Previous pavement-related experience of the consultant	0.1424	4
	Past experience and skills for pavement-related practices of the client's inspection team	0.1395	5
	Previous experience of the client regarding rehabilitation of pavements	0.1368	6
	Cyclic record keeping and amendments	0.1325	7
Contractor's capability	Availability of trained supervisors and other managerial staff	0.1513	1
	Availability of skilled labour with the contractor	0.1481	2
	Cyclic checks performed by the contractor	0.1475	3
	Training and guidance of the contractor's team	0.1438	4
	Timely procurement of machinery by the contractor	0.14	5
	Past experience of contractor pertaining to pavements	0.1392	6
	Subletting the work to subcontractors	0.1301	7
Organisational structure	Technical assessment of contractor on bidding	0.1507	1
	Quality management plan availability and accessibility	0.1469	2
	Procedures for training of staff and workers	0.1458	3
	Pavement-related quality standards availability and accessibility	0.1452	4
	Clarity of allocation of responsibilities and capabilities	0.1384	5
	Coordination and communication among officials	0.1388	5
	Performance measurement procedures for officials	0.1341	6
Payment and finances	Smooth cash flows	0.1806	1
	Escalation in prices of materials and machineries	0.1688	2
	Availability of finances for machinery with the contractor	0.1654	3
	Timely availability of finances to pay the labours	0.1643	4
	Timely availability of finances for payments to subcontractors	0.1637	5
	Reserves availability for any accidental/non-estimated expense	0.1572	6
Site management	Availability of consultant for quality control at the site	0.1832	1
	Availability of technical staff at the site	0.1725	2
	Availability of skilled labour at the site when needed	0.1716	3
	Timely availability of major machinery at the site when needed	0.165	4
	Timely availability of minor machinery at the site when needed	0.1617	5
	Discipline of site/managing disputes	0.146	6

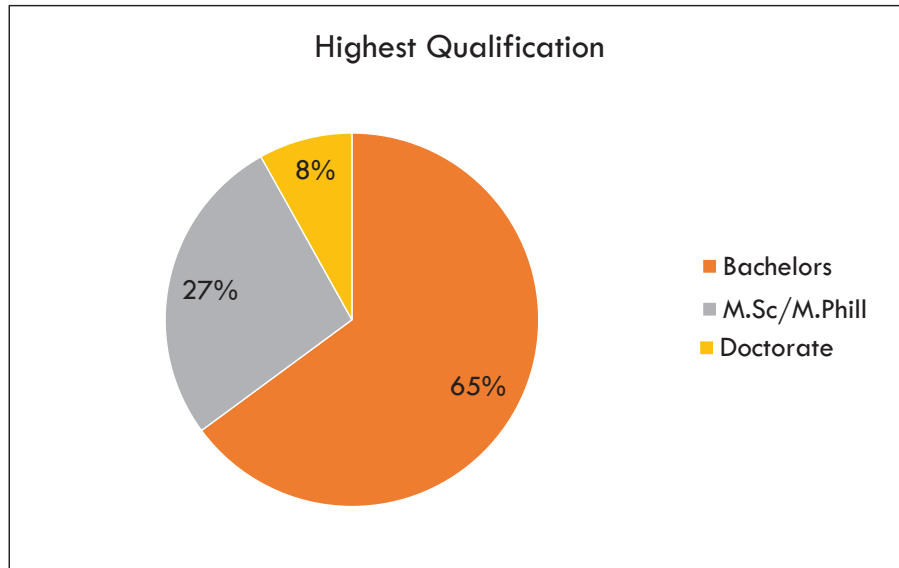


Fig. 2: Highest qualification of survey respondents.

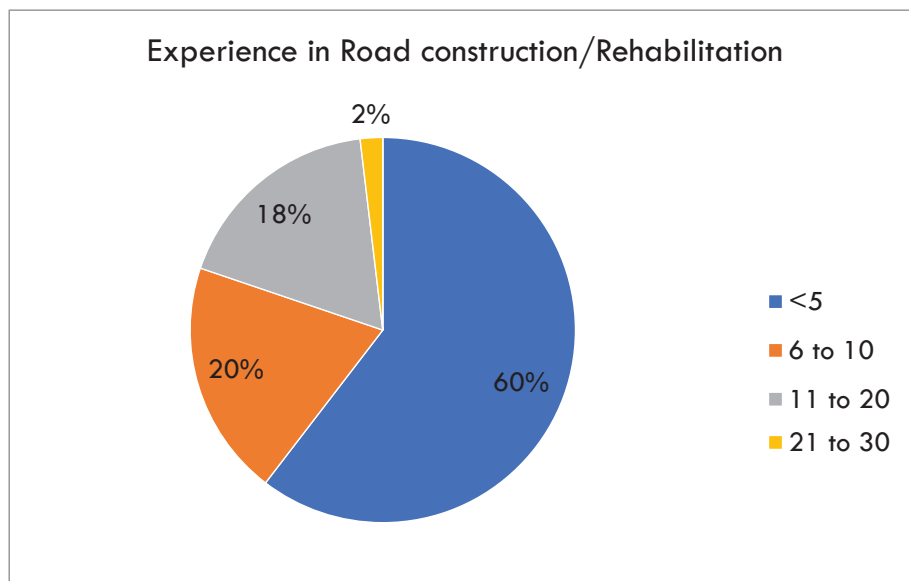


Fig. 3: Experience of survey respondents (in years).

of the surface, careful inspection of the milled surface with regard to profile level and others enlisted in Table 2.

Brooming and cleaning of milled surface to ensure its cleanliness from any loose material and dust particles, is important in ensuring good bond with the new asphaltic concrete layer (Mohammad et al. 2010). Brooming-related sub-factors that contribute to overall pavement quality include the appropriate use of air compressor, the use of hand brooms for left over dust in comparatively less accessible pavement areas and others shown in Table 2. Dust particles on the milled surface must be minimised to

keep the surface conditions suitable for tack coat application. Due to this, proper supervision on site by the skilled personnel during the rehabilitation works is necessary (Yaacob et al. 2014).

The presence of water/moisture in the surface over which the asphaltic concrete layer is to be laid is detrimental, as it weakens the bond and may also lead to stripping of the asphalt from the aggregate. Improper drainage leads to excessive percolation of water into layers of pavements. The presence of unwanted water may also cause premature failure (Ghasia et al. 2019). Key aspects

that ensure good sub-surface drainage include cutting of temporary drainage channels in shoulders and maintaining their appropriate spacing, ensuring design cross slope and others enlisted in Table 2.

Efficient crack repair on the milled surface is essential because if they are left untreated appropriately (i.e. cleaned and sealed), premature reflection cracking is expected to occur in the new pavement layer. Deeper milling and subsequent patching may be required where crack depth and extent exceed the threshold criteria. Cracks are one of the major challenges associated with the rehabilitation of pavements (Dhakal et al. 2016). Key crack repair and patching-related sub-factors that affect pavement quality include appropriate grooving, cleaning and sealing of cracks, use of efficient patching techniques keeping in view depth and extent of cracking and additional sub-factors as shown in Table 2.

The vital role of tack/prime coat in ensuring good bond strength in pavement layers and, indeed, the pavement quality is imperative. Therefore, ensuring the quality of tack/prime coat is essential in attaining good quality of finished asphalt concrete surface (Dharmarathna 2018). Tack coat type, rate of application, time of curing, temperature, availability of moisture and texture of surface are the major factors that influence the interlayer bonding (Wang et al. 2017). Proper tack coat application between the layers improves the durability of pavements (Somé 2021). Bond strength and interlayer friction are directly related to the application of the tack coat (Anh 2022). Important sub-factors regarding tack/prime coat application are shown in Table 2.

The quality of pavement is greatly influenced by the factors involved in the transportation of asphalt concrete from the plant to the paver at the laying site. Delays in HMA production and its application result in cooling of the mix, temperature segregation and ageing of bitumen. Asphalt stiffness rises because of the elongated time of loose mix before compaction (Bocci et al. 2020). Long hauling distances result in hardening of HMA, early brittleness in asphalt concrete and subsequently reducing the life of pavements (Hayat et al. 2019). Some of the important sub-factors are avoidance of asphalt concrete heat loss, compatibility of paver and dumper size and avoidance of asphalt concrete segregation and lumps (Table 2).

Discrepancies during the paving operation adversely affect the quality of the pavement. Regular monitoring of the paving procedure is important for good quality of asphalt pavements (Makarov et al. 2020). Significant aspects in this regard that influence the pavement quality include visual inspection of asphalt concrete, placing asphalt concrete at the appropriate temperature,

consistency of asphalt layer thickness, appropriate setting of paver machinery and more enlisted in Table 2.

Meticulous execution of transverse and longitudinal construction joints during pavement rehabilitation and construction is vital in ensuring the quality of the pavement. The initiation of deterioration from joints is a serious problem in asphalt pavements (Du-Tertre et al. 2022). Joints are inevitable in asphalt pavements, and proper compaction of the asphalt layer must be done to execute the joints properly (Roozbahany et al. 2013). Salient sub-factors related to the execution of joints that are expected to considerably affect pavement quality comprise cleanliness of dust, tack coat application, staggering of joints, appropriate preparation of cold joints, and additional factors as given in Table 2.

The compaction of the asphalt pavement determines the final quality of the pavement (Cantisani et al. 2016). Major failures in asphalt pavements have been attributed to poor compaction (Gao et al. 2018). Some of the compaction-related sub-factors that greatly contribute to the desired pavement quality encompass appropriate speed and trips of rollers, overlapping and rolling sequence, maintenance of rolling temperature, continuous post-rolling inspection of pavement and appropriate testing for compaction (Table 2).

The culminating step before opening the road to traffic after construction/rehabilitation is the fulfilment of road opening requirements. The quality of the freshly laid pavement may be compromised if these requirements are not adequately addressed. The early opening of the roads to traffic leads to fast deterioration of the rehabilitated pavement because insufficient bond strength between the layers and high temperature are not enough to resist heavy loads (Chu and Fwa 2020). Adequate cooling and settling time must be given to the recently laid asphalt layer to prevent the development of premature damage (He et al. 2020; Rahman et al. 2020). Key aspects that must be ensured before opening traffic to a freshly laid pavement, include; but are not limited to; adherence to desired roughness level (in terms of international roughness index [IRI]), provision of appropriate pavement rest period to ensure cooling of asphalt concrete to desired temperature and grinding of high spots (Table 2).

5.2 Main and sub-factors affecting pavement quality from managerial perspective

Since the contractor is directly involved in pavement construction/rehabilitation, its capabilities are believed to considerably influence the pavement quality. White

(2018) revealed that contractors are considered more accountable for the performance of pavements, and the availability of a competent contractor is important to ensure the quality of pavement rehabilitation/construction. The contractor needs an efficient team to manage the site quality and maintain customer satisfaction (El-Maaty et al. 2016). Key sub-factors related to contractor's capabilities comprise the timely availability of machinery, presence of trained supervisors and management staff, skilled labour, training and guidance of the team, subletting the works to sub-contractors, regular checks by the contractor and the contractor's experience pertaining to pavement rehabilitation and construction (Table 3).

Timely availability of funds leads to smooth cash flow. This, in turn, ensures uninterrupted availability of good quality material, skilled labour/staff and well-maintained machinery. Efficient finances also lead to timely payment to sub-contractors and availability of reserve funds for unforeseen circumstances. Insufficient investment in construction projects results in high long-term economic costs (Yepes et al. 2016). Adequacy of funds and proper planning are necessary to avoid poor construction quality of pavements (Hasan and Sobhan 2020).

Site management is an important factor influencing the quality of pavement construction/rehabilitation. It is important to ensure the management of the site and access of information to the workers to ensure efficient quality control (Harris et al. 2021). Asphalt concrete compaction is directly related to the availability of experienced field staff (Hayat et al. 2019). Sub-factors related to site management that are expected to affect pavement quality include the management of required machinery (major and minor), presence of labour when needed, availability of staff at the site when needed, appropriate employment of quality control consultant at the site and efficient resolution of site issues (Table 3).

The client's capabilities are important to ensure the overall quality of pavement because the client selects the contractors and consultants and gets the assigned tasks accomplished by them (El-Maaty et al. 2016). The client's financial and technical capability and stability directly influence the performance of contractors and consultants. The quality consultant's role in ensuring good quality pavement is vital because the client is the custodian of pavement quality from the start to the end of the project. The client and quality consultant are considered as one main factor, as it is a usual practice for the client to appoint the quality consultant for supervision of works performed on site and to make it accountable for

reporting the onsite quality situation. Usually, the documentation regarding approval of works is submitted to the consultant who acts as a representative of the owner/client (Rumane 2017; Thorpe and Sumner 2017; Tayeh et al. 2020). It then depends on the client to take the necessary actions. Client's and quality consultant's capability-related subfactors influencing pavement quality include; client's past experience and financial capability, past experience and training standard of quality consultant's team, efficiency of quality testing, and other factors shown in Table 3.

Organisational structure at every tier, that is, client, consultant and contractor, influences the quality of pavement construction and rehabilitation. Organisational structure in pavement maintenance companies needs significant improvements (Karim and Magnusson 2008). A well-established organisational structure results in better quality of product due to higher efficiency of works performed (Mwangi 2016). The availability of a well-established and trained hierarchy of key managers, appropriate quality control and performance measurement procedures and good coordination and communication protocols are some of the important factors related to organisational structure that affect the quality of construction projects in general and pavement construction and rehabilitation in particular (Table 3).

6 Weighting and ranking of main and sub-factors

The main factors and their sub-factors affecting pavement construction and rehabilitation quality, from constructional practices and managerial perspectives, are presented in Tables 2 and 3, respectively. Weights were assigned to each main factors and sub-factors based on the survey results, that is, average rating provided by the respondents. Eq. (1) is used for the calculation of the assigned weights.

$$\text{Assigning weights (W)} = \frac{\sum(R)}{5 * N} \quad (1)$$

R = Rates assigned out of five on five-point Likert scale by the respondents

N = number of respondents

The ranks were determined for each main and sub-factor based on the assigned weight, and the ranking of sub-factors within each main factor was also carried out, as presented in Tables 2 and 3. Table 4 shows the weights

Tab. 4: Mean ranks and weights of the main factors affecting pavement construction and rehabilitation quality.

Main factors	Minimum	Mean score	Maximum	Rank	Weights for main factors
Paving practices	1	4.52	5	1	0.0736
Compaction practices	2	4.47	5	2	0.073
Sub-surface drainage system	1	4.33	5	3	0.0705
Client's and quality consultant's capability	1	4.32	5	4	0.0703
Payment and finances	2	4.300	5	5	0.0700
Contractor's capability	1	4.21	5	6	0.0686
Site management	1	4.16	5	7	0.0678
Transportation of material	1	4.13	5	8	0.0673
Prime coat/Tack coat application	1	4.1	5	9	0.0668
Execution of joints	1	4.05	5	10	0.066
Brooming and cleanliness	2	4.01	5	11	0.0653
Milling methodology	1	3.86	5	12	0.063
Organisational structure	1	3.77	5	13	0.0614
Crack repair	1	3.75	5	14	0.0611
Fulfilment of road opening requirements	1	3.4	5	15	0.0554

and the minimum as well as maximum value assigned to all the main factors based on the questionnaire survey. The ranking was performed after the calculation of weights carried by each main factor.

7 Pavement construction/ rehabilitation quality index

The weights assigned to each main factor and sub-factor were used to develop a quality index formula-based matrix, which yields a quantified level of quality achieved in pavement construction and rehabilitation. The following equation yields the quality index that is contributed by the m^{th} main factor and i^{th} sub-factor in percentage.

$$\text{Quality index (\%)} = \sum W_m \times S_m \left(\frac{\sum (W_i \times S_i)}{25} \right) \times 100 \quad (2)$$

Where:

S_i = Score given at a project to the i^{th} sub-factor

W_i = Weight of the i^{th} sub-factor

W_m = Weight of the m^{th} main factor

S_m = Score given at a project to the m^{th} main factor

The quality of pavement rehabilitation and construction can be rated according to the value achieved in percentage. Values up to 60% were classified as low quality, values from 61% to 70% are considered fair quality, 71% to 80% represent moderate quality, 81% to 90% fall in the range of good quality and excellent quality is represented by values ranging from 91% to 100%. These ranges may

be customised according to the preference of the project/ organisation.

8 Application of the quality index on a project (case study)

To evaluate the practical application, the quality index-based methodology developed in this study was implemented on a real-life rehabilitation project on the M-2 (Islamabad-Lahore) Motorway in Pakistan to rate the quality of pavement rehabilitation. It is a 350-km-long, six-lane motorway, which was rehabilitated by resurfacing with HMA. The distressed asphalt-wearing course was milled, and a new asphalt-wearing course was laid in this rehabilitation project. The asphalt base course was also milled/removed and treated at selected locations along the motorway. Crack treatment on selected areas of the milled surface was also included in the scope of this rehabilitation.

All the sub-factors under each main factor (Tables 2 and 3) were shared with a group of 30 experienced individuals who were directly involved in the project from the inception phase to its completion. Each main and sub-factor was rated by these individuals according to its real-time application in light of their experience throughout the execution of the M-2 Motorway Rehabilitation Project. All the rates were then put in the index formula, and the average quality index value was calculated. The value of the quality index for this project was estimated

to be 76.43%, which falls in the range of moderate quality. The results of this case study can be effectively used as a guideline to improve particular main and sub-factors to enhance the overall quality of pavement rehabilitation and construction in future projects.

To analyse the validity of the developed quality index, the content validity index (CVI) was used in this research. CVI is considered essential to support the validity of a tool, such as a questionnaire designed for research. Validation of the content must be performed in a systematic way, based on reliable data and logical evidence (Yusoff 2019). CVI was implemented for the values between 71% and 80%, as the value of the quality index achieved for the case study was considered to fall under the moderate classification (76.43%). Total agreement came out to be 25 out of 30, and the values of the quality index for the remaining five individuals were between 81.1% and 83.5%. The value for $S - CVI/UA$ and $S - CVI/Ave$ both came out to be 0.833, which is considered to be highly valid (Shi et al. 2012).

9 Sensitivity analysis

To explore the sensitivity of important main and sub-factors to overall quality in terms of the quality index, a sensitivity analysis was carried out based on the key parameters developed in this research (weights of main and sub-factors). Variations in the quality index value obtained by the assignment of values/rates (0–5) to each of the top sub-factors, selected from the six most important main factors, were observed using the developed quality index formula. The values of the selected sub-factors were changed from 0 to 5, individually, while keeping the value of the rest of the sub-factors and main factors constant in accordance with the mean of the actual score assigned by respondents in this research. According to the overall ranking of main factors, the following six sub-factors (top sub-factor from each of the overall top six main factors) were selected for sensitivity analysis.

1. Availability of trained supervisors and other managerial staff
2. Achieving 97%–98% of laboratory compaction/material density
3. Financial capability of client
4. Smooth cash flows
5. Maintenance of design x slope for surface runoff
6. Use of appropriate method for achieving the design profile

Similarly, the sensitivity of the quality index to the top six main factors was analysed while keeping the values of the rest of the main factors and sub-factors constant according to the values assigned by the respondents during surveys. The following main factors were selected.

1. Paving practices
2. Compaction practices
3. Sub-surface drainage system
4. Client's and quality consultant's capability
5. Payment and finances
6. Contractor's capability

The effect on the overall quality index in response to variations in the rates of selected sub-factors is exhibited in Table 5 and Figures 4 and 5. The rightmost column of Table 6 shows the difference between the quality index values obtained after assigning the maximum rate to the selected sub-factor (i.e. five) and the maximum value of quality index (i.e. 100%) which could be obtained if the system was ideal/perfect. The lower the difference, the higher the importance of the sub-factor, that is, the closer the system is to the ideal conditions. Based on the sensitivity analysis results, Figures 4 and 5 show the variation in quality index values in response to an increase in rates of two sub-factors (from 0 to 5), that is, 'achieving 97%–98% of laboratory compaction/material density' and 'availability of trained supervisors and managerial staff', respectively.

Table 5 also shows the change in quality index value on each rise from 0 to 5 for each selected sub-factor. It is observed that on changing values for the sub-factor 'achieving 97%–98% of laboratory compaction/material density', the quality index value increases by 0.0808% for each increase in rate by one (from 0 to 5), which is the lowest among the selected sub-factors despite the fact that it was selected from the main factor 'Compaction practices', which is ranked second in importance according to the ranking mentioned in Table 4. Relatively, among the selected sub-factors, 'availability of trained supervisors and managerial staff' exhibits the highest impact by contributing 0.175% to the quality index value on each rise of the rating from 0 to 5, while this is the top sub-factor of the overall top sixth main factor 'Contractor's capability', as shown in Table 4.

Similarly, the effect of variations on the overall quality index for the selected main factors can be observed in Table 6 and Figures 6 and 7. The rightmost column of Table 6 shows the difference between the quality index values obtained after assigning the maximum rate to the selected main factor (i.e. five) and the maximum value of

Tab. 5: Comparison of quality index values obtained from sub-factors.

Top 6 Sub-factors	Assigned Value/Rate						Difference between index value after each rise from 0 to 5	Difference of maximum index value from 100%
	0	1	2	3	4	5		
Availability of trained supervisors and other managerial staff	65.385	65.56	65.735	65.91	66.085	66.26	0.175	33.7400
Achieving 97%–98% of laboratory compaction/material density	65.7796	65.8604	65.9412	66.022	66.1028	66.1836	0.0808	33.8164
Client's and quality consultant's capability	65.3143	65.5043	65.6943	65.8843	66.0743	66.2643	0.19	33.7357
Smooth cash flows	65.1903	65.4078	65.6253	65.8428	66.0603	66.2778	0.2175	33.7222
Maintenance of design cross slope for surface runoff	65.2948	65.4907	65.6866	65.8825	66.0784	66.2743	0.1959	33.7257
Use of appropriate method for achieving design profile	65.66	65.7685	65.877	65.9855	66.094	66.2025	0.1085	33.7975



Fig. 4: Quality index values for sub-factor: 'Availability of trained supervisors and other managerial staff'.

quality index (i.e. 100%) which could be obtained if the system was ideal/perfect. Figures 6 and 7 show the variations in quality index values in response to an increase in the rates of top two selected main factors (from 0 to 5), that is, 'Paving practices' and 'Compaction practices'.

The sensitivity analysis results for the main factor 'paving practices' show that the quality index increases by 1.22%, which is the highest as compared to the rest of the selected main factors. This shows that as the rate increases from 0 to 5, the main factor 'paving practices'

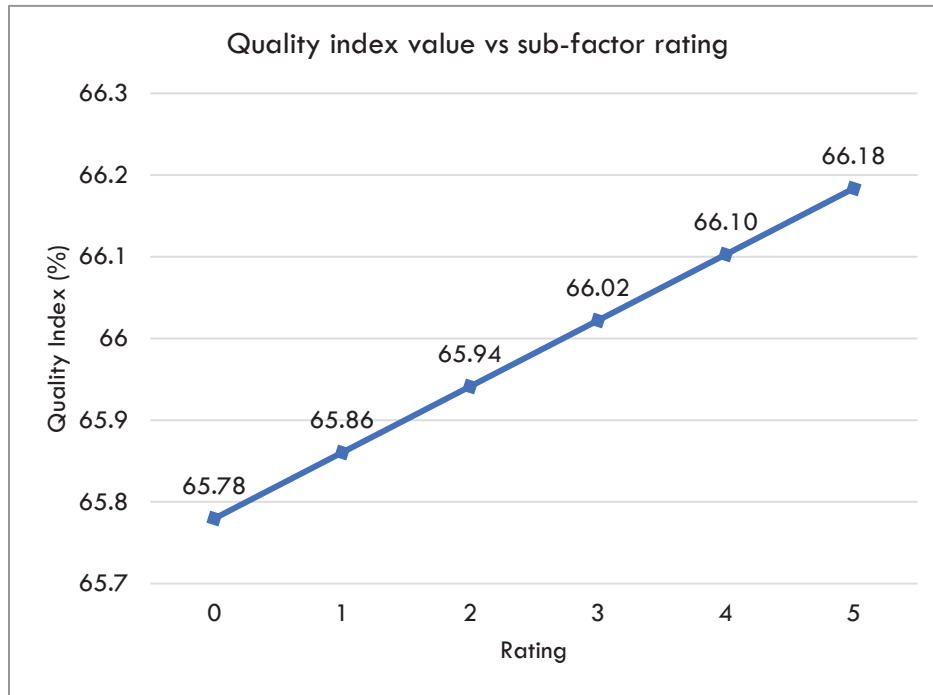


Fig. 5: Quality index values for sub-factor: 'Achieving of 97%–98% of laboratory compaction'.

Tab. 6: Comparison of quality index values obtained from main factors.

Main factors	Assigned Value/Rate						Difference between index value after each rise from 0 to 5	Difference of maximum index value from 100%
	0	1	2	3	4	5		
Paving practices	60.622	61.842	63.062	64.282	65.502	66.722	1.22	33.278
Compaction practices	60.683	61.902	63.121	64.34	65.559	66.778	1.219	33.222
Sub-surface drainage system	61.446	62.53	63.614	64.698	65.782	66.866	1.084	33.134
Client's and quality consultant's capability	61.33	62.441	63.552	64.663	65.774	66.885	1.111	33.115
Payment and finances	61.3	62.422	63.544	64.666	65.788	66.91	1.122	33.09
Contractor's capability	61.443	62.5574	63.6718	64.7862	65.9006	67.015	1.1144	32.985

shows the highest impact on the quality index after each rise by one (from 0 to 5). For the main factor compaction practices, the analysis shows that the difference for each rise is 1.219%, which is the second highest among the selected main factors. The data from the sensitivity analysis for main factors show that the effect of each main factor on the rise from 0 to 5 is in accordance with the ranking done for the main factor in this study.

Hence, it is revealed that, unlike main factors, the sub-factors under the top-ranked main factors may not have a higher impact on the overall quality index value compared to the sub-factor that may belong to a comparatively lower-ranked main factor, and each sub-factor has its significance on the overall quality index, irrespective of the rank of its main factor. The quality index equation developed in this study, therefore, duly encompasses the

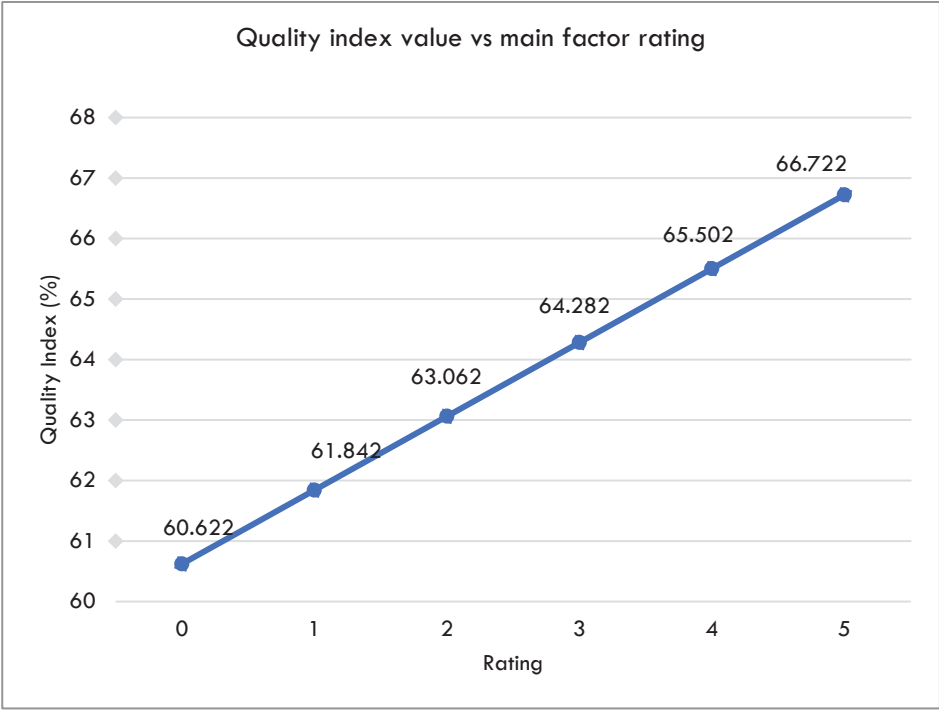


Fig. 6: Quality index values for the main factor: 'Paving practices'.

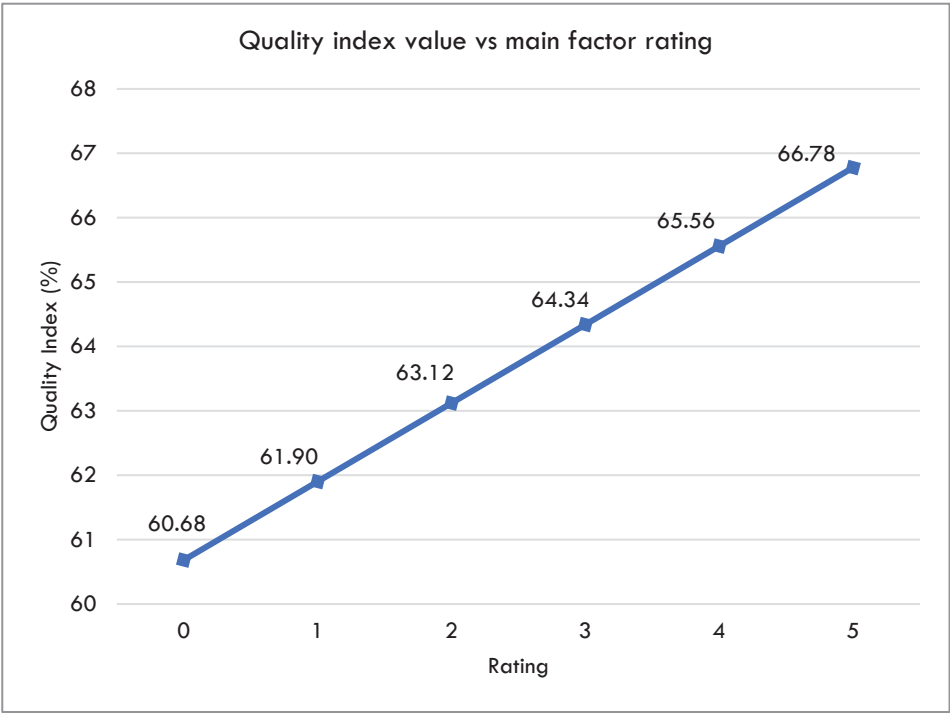


Fig. 7: Quality index values for the main factor: 'Compaction practices'.

impact of each sub-factor and main factor, collectively, on the overall quality index.

10 Results and Conclusions

This study presented a methodology of quantifying the quality of pavement construction and rehabilitation, duly considering the important quality-influencing factors from managerial and constructional perspectives in terms of a quality index. The practical application of the developed index was evaluated and validated through a case study. The influence of selected factors on overall quality was explored through a sensitivity analysis. The results of this research can be effectively used, as a guideline, checklist and yardstick, to improve particular main and sub-factors in order to enhance the overall quality of pavement rehabilitation and construction in future projects.

A review of the literature revealed that there is a severe lack of research on the quantification of pavement construction and rehabilitation quality, duly considering the important quality-influencing factors from managerial and constructional perspectives. Very little emphasis has been laid on the evaluation of factors affecting the quality of pavement construction and rehabilitation from a constructional practices perspective in past research. There is a dire need to develop a methodology to quantify the quality of pavement construction and rehabilitation from managerial and constructional perspectives, in terms of quality rating/index.

A rigorous literature review and a meticulous pilot survey based on analysis of experts' opinions and interviews yielded a comprehensive survey questionnaire, duly considering the important pavement construction and rehabilitation quality-influencing factors from managerial and constructional perspectives. A pavement construction and rehabilitation quality quantification matrix, yielding quality in terms of a quality index, was developed based on the assigned weights to the selected 15 main and 131 sub-factors.

Ranking analysis of survey data revealed the following top six main pavement construction and rehabilitation quality-influencing factors in order of priority:

1. Paving practices
2. Compaction practices
3. Sub-surface drainage
4. Client's and quality consultant's capability
5. Pavement and finances
6. Contractor's capability

The following top six ranked important sub-factors affecting the quality of pavement construction and rehabilitation were identified, consequent to the analysis of results of this study:

1. Cleanliness of milled surface from loose material, dust, droppings and residuals
2. Proper use of equipment
3. Dryness of the surface
4. Brooming before every prime/tack coat application
5. Availability of consultant for quality control at site
6. IRI should be ≤ 1.5 m/km

Practical application of the developed quality index formula through the case study revealed that the rated quality of the M-2 Rehabilitation Project was 76.43%, which demonstrated moderate quality. CVI analysis on the case study data revealed total agreement of 25 out of 30 individuals, which represents high validity.

Sensitivity analysis revealed that, unlike main factors, each sub-factor has its individual significance on the overall quality index, irrespective of the rank of its corresponding main factor, and the quality index equation developed in this study duly encompasses the impact of each sub-factor and main factor, collectively, on the overall quality index.

11 Research implications and contribution

Results of this research can be effectively used, as a guideline, checklist and benchmark, to improve and address particular main and sub-factors, yielding enhanced overall quality of pavement rehabilitation and construction in future projects, duly considering the constructional and managerial perspectives. This is one of the pioneer studies that comprehensively considers the factors affecting the quality of pavement construction and rehabilitation from both constructional and managerial perspectives. This study also attempts to take the lead in presenting a methodology to quantify the quality of pavement construction and rehabilitation, in terms of quality index, duly cognisant of the main factors and sub-factors affecting quality from constructional and managerial perspectives. This research addresses the indicated critical research gap between the theoretical and practical aspects of quality of pavement construction and rehabilitation.

12 Recommendations

The identified factors should be mandated for site inspectors to ensure thorough and efficient inspections. The developed quality index, tailored to meet industry standards, should be promptly implemented. Recognition of the importance of pavement rehabilitation at the governmental level is imperative. Government records should meticulously document quality incidents and associated costs, with a system in place to verify their accuracy. Companies and government bodies alike should establish structured protocols for managerial oversight, incorporating both incentives and penalties. A centralised data collection system is essential for continuous analysis and updating of quality-related incidents and expenses. Government audits should rank companies based on quality performance, guiding contract awards accordingly. Regular assessments utilising the quality index should be conducted annually to prioritise companies. The quality index template can be applied comprehensively or to specific project phases, such as pre-compaction factors. Similar studies should extend to various construction sectors, addressing not only quality but also safety, risk and time management.

Similar further research should be conducted for other fields of construction, such as building construction, safety, etc. This study is related to HMA pavements; future research is recommended to be conducted for rigid pavements. As this study is one of the pioneer studies, it is highly recommended to introduce automation in the quantification of pavement rehabilitation and construction quality. A tool must be developed based on software and drone-regulated assessment of on-site quality. This will not only reduce the involvement of individuals but also minimise the associated errors. This requires considerable efforts from the government so that constructed roads can serve their purpose for their full design life.

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