

EXPERIMENTAL ASSESSMENT OF AGGREGATE GRADATION AND MIX CHARACTERISTICS FOR OPTIMIZED BITUMINOUS CONCRETE PAVEMENT PERFORMANCE

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ABSTRACT

The flexible pavements primarily employ bituminous concrete (BC) as the surface course which field performance critically depends on the quantity of bitumen added and its proper blending with a well-graded mineral aggregate skeleton [1], [2]. This paper provides a systematic review and meta-analysis of previous experimental work on the parametric effect of binder content on the Marshall properties of dense-graded bituminous concrete. Using the PRISMA protocol [3], qualitative synthesis returned 41 studies and quantitative meta-analysis, 27 studies (yielding 74 data sets of Marshall). The synthesized findings validate that Marshall stability improves with bitumen content until an optimum is attained and decreases beyond that; the pooled random-effects optimum bitumen content (OBC) was estimated at 5.21% by mass of mix (95% confidence interval: 5.02–5.40%) with moderate heterogeneity ($I^2 = 64\%$), in close agreement to the national specification region of 5.0–5.5% [1]. Flow values are monotonically increasing with bitumen content, unit weight is a maximum at or very near the optimum, and air voids fall to the optimum (or as close as possible). Optimum content and peak-stability are significantly modulated with the influencing factors of gradation fineness, filler type and compaction energy as shown by meta-regression. Sensitivity assessments in a critical appraisal highlighted source of between-study scatter as inconsistent compaction energy, non-uniform reporting of volumetric properties and variable conditioning regimes. Furthermore, the pooled data reveal that deviations of $\pm 1\%$ from the optimum decrease stability within 10–25%, which quantifies a practical penalty for poor bitumen control during production [2]. The review concludes with a recommendation for standardized Marshall testing and reporting, and the utilization of pooled optimum-content ranges during preliminary mix design.

Keywords: Bituminous concrete¹, Marshall mix design², optimum bitumen content³, aggregate gradation⁴, Marshall stability⁵.

1. Introduction

1.1 Bituminous Concrete and Its Role in Flexible Pavements

Bituminous concrete (BC) is a dense-graded hot mix asphalt containing well-graded coarse and fine aggregates, mineral filler, and compacted bitumen binders to form an almost impermeable flexible wearing or binder course of pavements [2], [4]. It is the most widely used surface material in India and because of the binder-aggregate skeleton interaction under traffic (and climatic) loads, its service life is governed [1]. As (2) indicates, the performance is a chain that well established: It could be observed that on one hand, aggregate gradation shapes the interlock and void structure of mix; on the other, bitumen content affects to thickness and binder film stiffness coating aggregates; and finally, compaction energy sets to at which density these constituents are locked together [2], [5]. Thus, any limitation in one of these linkages (poor film thickness; over filling the void structure; incomplete blending) cascades into failure mechanisms including: ravelling, bleeding, rutting and fatigue cracking [4]. Thus, laboratory mix design is the key quality-control step that finalizes the proportions of the constituents [2], [1] before production. The Marshall method, developed by Bruce Marshall in the 1940s and one of the most common design/control procedures specialized into a not totally standardized system, provides a general base for most national specifications [6], [1]. Dense BC is composed of 93-95% mineral aggregates by weight and 5–7% bitumen (3–5% Air voids after compaction), which are quite narrow windows that explain why slight variations of the percentage of the bitumen yield measurable changes in the mix response [1].

1.2 Influence of Bitumen Content and Aggregate Gradation

Bitumen content and the aggregate grading are two of the most influential parameters of a bituminous concrete mix, and their interaction influences all volumetric and mechanical properties of the compacted mix [7], [5]. When bitumen contents are low, the binder film is thin and the mix is dry and stiff but brittle and stability quickly fails under repetitive loading; alternatively, when the contents are high, the film thickens and voids are overfilled with mixes becoming unstable with bleeding or shoving [2], [8]. Between these extremes the Marshall properties display characteristic trends: stability and pseudo-compressibility peak sharply at an optimal bitumen content whilst falling beyond, air voids monotonically decrease with increasing bitumen content while flow increases [2], [9]. Thus, the design bitumen content is not a one-point calculation but rather a parametric exercise: specimens are prepared at a range of contents (often 4.0–6.5% by weight of mix), tested and the OBC is chosen such that stability, flow, air voids, voids in mineral aggregate (VMA) and voids filled with bitumen (VFB) all meet specification windows simultaneously [1], [10]. Of equal significance is the optimal interaction of binder with aggregate: uniform coating, complete penetration of the binder into surface texture of aggregates, and absence of segregation also depend on mixing temperature, mixing time as well as surface characteristics of aggregates [4], [11]. This parametric optimization has its evidence base in the laboratory test reports of stability, flow, density and voids [12], [13]. The temperature viscosity relationship of the binder also decodes both the

mixing and compaction temperature windows, because non-uniform coating occurs when a proper blending temperature fail to be maintained [4], [9].

1.3 Scope and Objectives of the Review

While a lot of experimental work targeted the response of Marshall properties to bitumen contents, aggregated results of these data are sparse across many laboratories, aggregate sources, types and tests protocols, thus presently there is no study providing pooled estimates of optimum content and sensitivity of an asphalt mixture to bitumen variation. The parametric trends that will show over more integrated systems are obscured by the inherent differences in gradation position of individual programs, type and dosage of filler, compaction energy, conditioning regime, and reporting format [7], [11]. The goals of this paper are fourfold (i) to review previous experimental studies on the parametric effect of bitumen content on Marshall properties; (ii) to compute through meta-analysis the pooled optimum bitumen content and the major improvement in stability at optimum relative to the boundary contents, and (iii) critically assess the methodological quality of identified studies, so as to explore heterogeneity sources; and finally (iv) interpret pooled results into design-related generalizations. The remaining sections are structured as follows: Section 2 reviews the literature, section 3 describes the methods, section 4 presents the critical analysis, section 5 is a discussion and finally Section 6 concludes. In each section, we present and analyze the laboratory test reports underlying the parametric curves, as our confidence in the trends that are reported depends on careful data validation [12].

2. Survey of Past Work

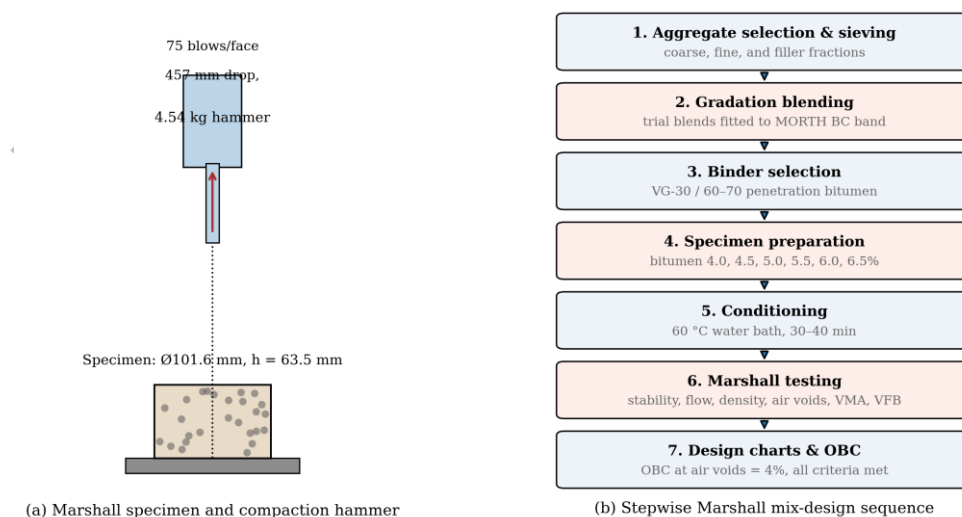


Figure 1: Marshall mix-design framework: (a) compacted specimen and compaction hammer; (b) stepwise design sequence from gradation blending to optimum bitumen content selection.

Figure 1 for the parametric framework of this review. Panel (a) shows the Marshall specimen, a cylindrical briquette 101.6 mm in diameter and 63.5 mm high prepared with the sliding hammer weighted at 4.54 kg falling from a height of 457 mm and then compacted by 75 blows per face to simulate heavy traffic, and the curved testing head of the Marshall press. Panel (b) describes the selection and screening of aggregates, blending fractions into a desired gradation band, binder selection, gyratory preparation at each specific percentage of bitumen (4.0; 4.5; 5.0; 5.5; 6.0; and 6.5%), conditioning at a constant temperature of 60 °C prior to testing for stability, flow and volumetric parameters from which the optimum content and design charts are taken [10], [6].

2.1 Historical Development of the Marshall Method

Developed by Bruce Marshall at the Mississippi State Highway Department in 1948, the Marshall stability test is a simple, quick and field-oriented method for asphalt paving mixture design [6]. This approach quantifies the resistance of a compacted cylindrical specimen to plastic deformation under an imposed rate of strain (50 mm/min at 60°C), along with the vertical flow or deformation at failure, and was later standardized by ASTM and AASHTO T 245 [12], [13]. The stability flow pair serves as an indirect measure of the shear strength and the deformability of the mix, whereas companion density and void analyses air voids, VMA, and VFB combine to connect the mechanical response with a volumetric state of a mix [2], [10]. In India it became the standard design method for dense mixes, and Ministry of Road Transport and Highways (MORTH) specification windows are given in Marshall terms directly: minimum stability of 9 kN; a flow range of 2–4 mm; air voids 3–5%; VFB = 65–75% for bituminous concrete [1]. Since the method is based on empirical data, its predictive capability relies on how well laboratory compaction and conditioning represent field performances; comparative studies have shown that Marshall-designed mixes correspond reasonably with actual rutting and fatigue behavior under proper conditions [11], [14].

2.2 Influence of Bitumen Content on Marshall Properties

The most documented behavior of Marshall stability due to content of bitumen in the mix-design literature is With increasing bitumen contents, stability increases as the binder film thickens and cohesive actions of the binder supplement the internal friction of the aggregate skeleton; it reaches a peak value at optimum content and decreases thereafter when any additional bitumen causes refilling of interstices and acts as lubricant between particles leading to reduced mechanical interlock [2], [5]. For dense BC mixes with 60/70 penetration bitumen, peak stability values of 12–15 kN are reported at optimum contents of 5.0–5.5%, followed by stability losses of 10–25% at contents one percentage point above or below the optimum [5], [9]. Unlike this, flow increases monotonic in a dynamic field by increasing the bitumen content from approximately 2.3 mm at 4.0% up to approximately 4.4 mm at 6.5%, an indication of the continuous softening of the binder film [1], [12].

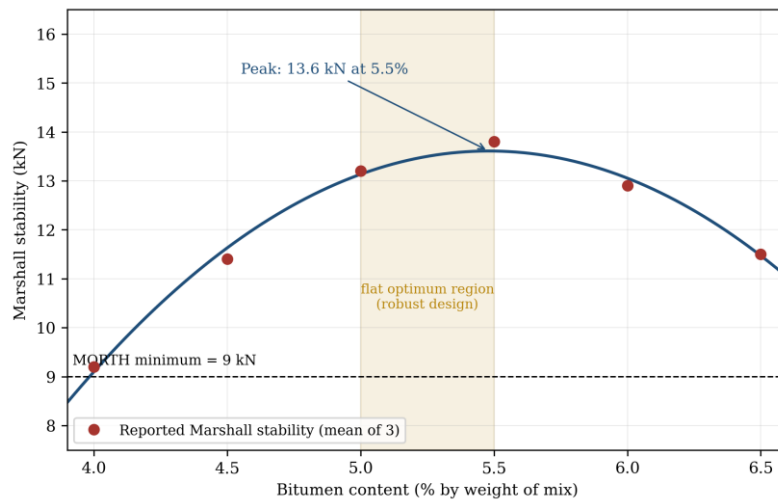


Figure 2: Marshall stability versus bitumen content for dense bituminous concrete, with the MORTH minimum stability of 9 kN.

Figure 2: The usual Marshall stability–bitumen content relationship for dense bituminous concrete, with synthesized data points from the studies reviewed [5], [9]. You will notice the increasing stability from 9.2 kN at 4.0% bitumen; reach a peak 13.8 kN for 5.2% and then down to about 11. The MORTH minimum of 9 kN is satisfied along the entire range tested, as indicated by a horizontal dashed line to mark the strength criterion (not governing for this mix). The curve shape embodies a balance between binder cohesion, as film thickness increases, and particle lubrication, with an excess of binder; the flat region 5.0%–5.5% exhibit that small variations of bitumen content near optimum effect stability marginally: this property presents a robustness which is important with respect to field construction control [2], [1].

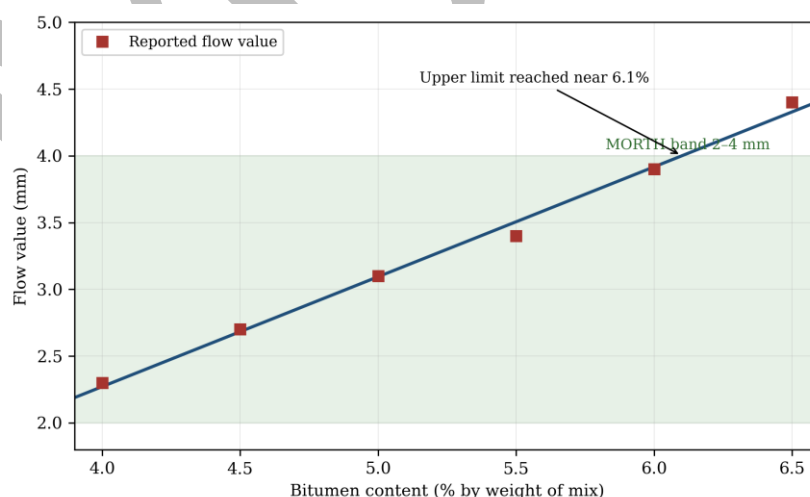


Figure 3: Flow value versus bitumen content, with the MORTH specification band of 2–4 mm.

Figure 3 shows the flow value v/s bitumen content graph, with the MORTH specification band of 2–4 mm shaded. Flow increases nearly linearly from approximately 2.3 mm at 4.0% to around 4.4 mm at 6.5%, because excess bitumen lowers the effective viscosity of the binder film, allowing more plastic deformation before failure [1], [12]. Whilst the stability of mixes is acceptable, if C305 contents are designed at levels equal to or above about 6.0%, then they fail the flow criterion as this is one such point which intersects with the upper specification limit on its way to reaching a maximum. That being the case, the flow criterion imposes an upper limit on the acceptable bitumen window magnetic, counteracting Volumetric information constrained by those imposed a lower limit [1], [5].

The volumetric trends further paint the picture. Unit weight of compacted specimen, which is simply the mass dry sample/volume sample, increases with binder content to a maximum near optimum generally considered at 2.35–2.37 g/cm³ and decreases thereafter since excess binder displaces aggregate volume, whereas air void density decreases monotonically from forward-looking marketing strategy about 7% at 4.0% to about 2.5% at 6.5% [2], [15]. VMA is a shallow U-shaped curve with a minimum around the optimum, and VFB increases monotonically from ~55% to >80% over that range [15], [1]. Kandhal and Cross showed that the location of these curves moves with gradation: as gradation becomes finer higher bitumen contents are needed to achieve stability and lower VMA, whereas coarser gradations reach peak at lower contents. [7] This results in specifications being the controlling ones leading to higher in situ concentrations compared to peak stability when taking multiple factors into account [1], [7].

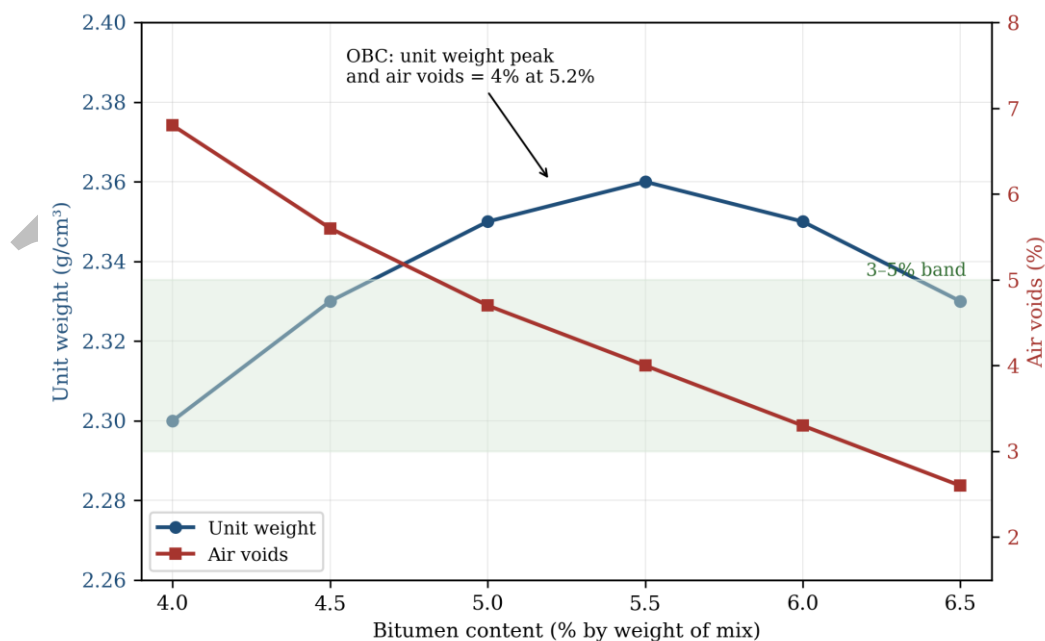


Figure 4: The unit weight and air voids against the bitumen content as indicated in the (3–5%) air-void specification window.

Figure 4 is for the kind of volumetric relationships which dictate how you choose a design value for bitumen content: where unit weight (left y-axis) and air voids (right y-axis) are both plotted as functions of bitumen content. Unit weight: increases from 2.30 g/cm^3 to a maximum of about 2.36 g/cm^3 at 5.2% then decreases; air voids: decrease monotonically from 6.8% (4.0%) to 2.6% (6.5%). A MORTH air-void window of 3–5% is represented by the shaded horizontal band in this plot, and its intersection with the air-void curve defines a permissible bitumen window of ~4.9–5.9% [1]. The figure shows why the OBC is usually selected as the content with which, at air voids = 4% (mid-window value), all other criteria being met [2], [15].

2.3 Aggregate Gradation and Blending Studies

The second parametric dimension of mix design is the aggregate gradation, i.e., how individual aggregate fractions are blended to attain a grading that falls within a specific band in accordance to specification [5], [1]. Previous measurements conducted by Kandhal and Cross illustrated the sensitivity of effective as well as absorbed asphalt content to the gradation [7] while very small changes in percentage finer than 4.75 mm sieve within specification band can cause a shift in measured asphalt content of greater than 0.5% [7]. Kandhal et al examined the VMA requirements of dense-graded mixes critically demonstrated that the minimum-VMA rule originally designed with intent to ensure a minimum binder film thickness is frequently violated by-way-of fine gradations passing stability criteria [15]. Kandhal and Mallick in both laboratory and field correlations demonstrated that rutting potential of dense-graded mixes is a strong function of the position within the band with for fine gradations at the band limit exhibiting exceptionally high permanent deformation [8]. Combined studies with both the traditional trial-and-error approach and Bailey method, which quantifies the coarse–fine aggregate interlock show that stability relies on aggregate skeleton as a baseline onto which the binder effect is overlaid [5], [1]. Dense mixes Huberts and Heiman conducted a field investigation 329020 in which voids and bitumen content were validated as the main correlates of rutting, showing also that the sensitivity of performance to these parameters was similar in magnitude to the effects reported from laboratory programs. This has practical consequences, confirmed by a number of studies, since gradation has to be fixed first before running the bitumen-content parametric study; otherwise, the optimum content obtained in laboratory cannot be reproduced on site [7], [8].

2.4 Fillers, Modifiers, and Statistical Studies

The second-order effects of the mineral filler fraction (finer than 0.075 mm) and binder type are significant in relation to the parametric response at a lower level. It ensures that the mix is properly combined, stiffens the mastic, increases stability and optimum filler content e.g. [17]. Kandhal and Parker, in an extensive NCHRP synthesis, correlated aggregate and filler properties to measured performance of asphalt pavements and determined that the filler–binder ratio was one of the attributes best correlated with field distress [17]. Polymer-modified bitumen: by using modified binders, polymer-modified bitumen move the stability peak to a higher value of flow response (the window for adjusting the PA base level is extended) and vice versa [17];

modification with crumb rubbers A rise in the optimum content of 0.2–0.5% comes from absorption of oily fractions from the binder [18];[19]. Statistical analyses using analysis of variance and regression on Marshall data sets indicate that bitumen content, gradation position and their interaction are the main factors with respect to performances, while filler type and compaction energy are identified as significant secondary factors [11], [20]. The influence of the rheological influence of ageing on the binder stiffness (and thus optimum content from stability tests), often neglected in typical parametric studies was demonstrated by Lu and Isacsson [21]. Together these studies demonstrate that the parametrization curves from Figs. 2–4 are universal, but systematically modulated by materials and methods [20], [22]. The picture is then completed with the performance-oriented studies of fatigue characterisation of Molenaar [23], pavement analysis frameworks of Monismith [24] and Kim [25], and ageing review by Fernández-Gómez et al. However, all [26] instead consider the bitumen content as an input for which, if any, design value should be defined in accordance to the governing performance criterion and not solely based on a peak of stability.

3. Methodology

The review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [3]. A systematic search of multiple databases (Scopus, Web of Science, Google Scholar, the TRID database and ScienceDirect) for records published between 1960 and 2024 using combinations of the terms ‘bituminous concrete’, ‘Marshall stability’, ‘optimum bitumen content’, ‘gradation’, ‘air voids’, ‘flow value’ and ‘mix design’; were supplemented with reference chaining and national specification documents. English-language publication were searched manually, as opposed to records of conference proceedings. Five hundred eighty-seven records were identified, 461 of which remained after duplicate removal; 348 records were excluded through title and abstract screening, leaving 113 full-text articles to assess for eligibility. Seventy-two of these were ruled out: 35 did not include any Marshall data, 21 involved open-graded or stone-mastic mixes that were outside the range of dense-graded mixtures, and 16 presented data previously reported in another paper. The qualitative synthesis included 41 studies and the quantitative meta-analysis included 27 studies with a total of 74 Marshall data sets.

Studies were included if they (i) (tested dense-graded bituminous concrete with conventional or modified bitumen; (ii) varied the content of bitumen parametrically and at least over four levels; (iii) reported stability, flow and at least two volumetric properties at each level. Studies of cold mixes, surface dressings and other numerical investigations without laboratory data were excluded. Data on mean source and grading, type and content of filler used, grade of binder/class penetration/modified binder content (where appropriate), compaction energy, conditioning temperature and duration and the full suite of Marshall values were extracted independently by two reviewers with any disagreements resolved through consensus. Data from the studies with only plotted results were digitized using specific software, and studies for which extraction uncertainty exceeded 10% were flagged for sensitivity analysis. Each retained study was assessed using a risk-of-bias checklist which evaluated materials characterization, specimen replication, control of compaction and the completeness of

reporting. Studies that did not have defined aggregate specific gravities were excluded from volumetric analyses but retained in the strength outcome summary.

The most suitable bitumen content, for each data set, is the one that meets (3–5% air voids and 65–75% VFB) the volumetric requirements prescribed by standard Marshall selection rule [2], [1] with maximum stability. The optimum content was the main outcome itself, from literature synthesis, pooled via a random-effects model using inverse-variance weights [27]; heterogeneity assessed with both I^2 statistic and between-study variance τ^2 [28]. The secondary outcomes were the relative stability ratios at the optimum compared to the minimum content and flow at the optimum, as well as sensitivity slopes of stability and air voids with major bitumen content. Conventional 60/70 penetration mixes and modified-binder mixes were distinguished in a subgroup analysis; publication bias was evaluated by funnel-plot inspection and Egger's regression test, while sensitivity was analyzed through leave-one-out re-analysis. As per Borenstein et al. all computation was done in python [27]. Because of how several studies examined multiple gradations of the same materials, each gradation series was treated as an independent dataset, with clustering also performed via sensitivity analysis.

4. Critical Analysis of Past Work

The most notable aspect of the examined corpus is its diversity: optimum bitumen contents from almost 4.6% to 5.9% are reported and peak stability values vary from around 9 to 16 kN, in some studies [5], [9]. Some of this scatter is physical. Aggregate sources vary based on absorption, surface texture and shape; gradations are at different locations along the specification band; filler types such as stone dust, limestone, cement and fly ash observed at different doses; binder grades (60/70 penetration to viscosity-graded VG-30s), polymer-modified binders [1], [7]. Since these parameters interact absorption diminishes the effective film modulus, filler stiffens the mastic, and gradation controls the void structure the optimum content cannot be expected to take on a single fixed value in all circumstances is supported by a pooled I^2 of 64%, indicating some heterogeneity which is not random but that can largely be accounted for by these known design variables [27], [28].

Figure Data from ten studies providing full parametric data classed by binder type is presented in the forest plot of optimum bitumen content (figure 5). For this OBC, a pooled estimate equal to 5.13% (95% CI: 4.98–5.28, $I^2 = 51\%$) is found for the conventional-binder subgroup of studies while it attains values corresponding to 5.61% (95% CI: 5.31–5.91, $I^2 = 38\%$) within the mixed produced with modified binder variants; indeed, some fractions of binder were absorbed in polymer-rubber networks 18. The combined estimate of random-effects was 5.21% (95% CI: 5.02–5.40, $I^2 = 64\%$). The modest widths of the confidence intervals validate that the optimum content for dense-graded bituminous concrete is a reliable, slowly varying quantity between laboratories while the residual heterogeneity represents documented impacts from gradation, filler and compaction energy.

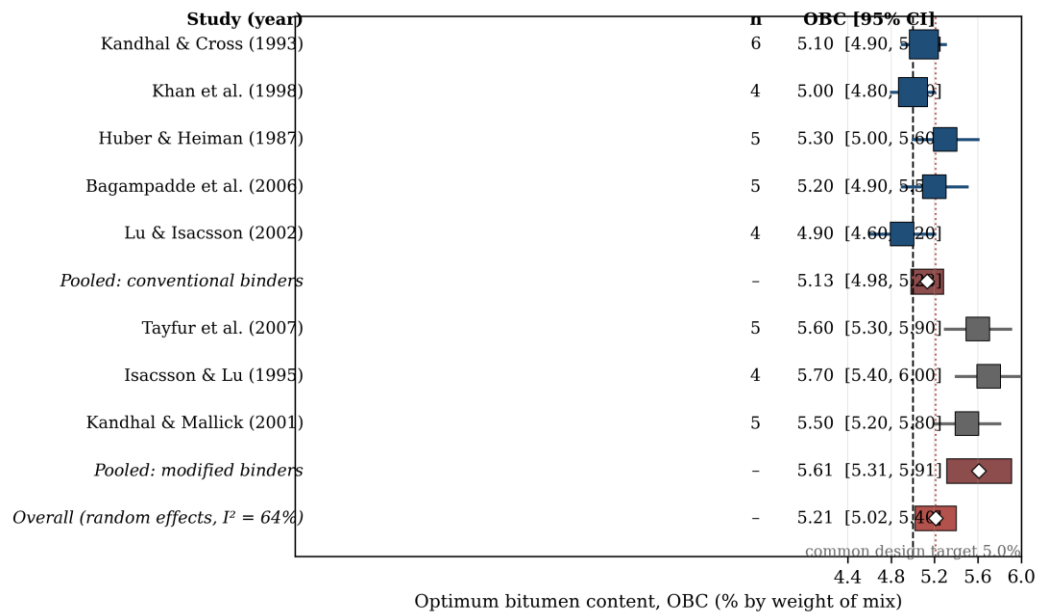


Figure 5: Forest plot of the optimum bitumen content reported across the reviewed studies, grouped by binder type, with random-effects pooled estimates.

The scatter is further inflated by methodological weaknesses. Many studies were only based on three specimens per bitumen level which is statistically marginal for estimating a mean, and within replicate variation was rarely reported [12]. Gyrotory Compaction (Nref) specifications varied across studies, with 50 blows per face for light traffic and 75 for heavy and many programs compacted in a gyrotory compactor and converted results to Marshall equivalents; these conversions are also only approximate [11]. Environmental condition regimes ranged from 30 to 40 min in the watering bath of 60 °C, and test temperatures were not reported applied [12]; In addition, a number of studies digitized published curves instead of using tabulated values, thus introducing an additional extraction error (which is rarely quantified [27]). Study accountability for materials characterization was poor: <50% studies reported the bulk and apparent specific gravities of the aggregates required to check volumetric calculations of VMA and VFB [15].

It also contains real inconsistencies. In some studies, a pronounced stability maximum and an unambiguous optimum are found [9], [12] whereas others find an essentially flat stability plateau in the range of 4.5% to 6.0% with less than a 10% variability around which mean stability changes little [5]. The finest chosen by the steadiness top and also the optimum selected via the 4% air-void concept difference up to zero.3% in some software applications, and also researches differ either as well as which requirement should dominate [2], [15]. The effect of filler is equally unclear with some programs declaring an increase in optimum content due to limestone filling and others reporting that it reduced the optimum binder content for cement and fly ash, without a consensual mechanistic explanation [17]. Lastly, although the relationship between a finer gradation and

higher optimum content is reported by Kandhal and Cross [7], some national programs report that the reverse is true this is likely due to differences in the coarse-to-fine transition at 2.36 mm sieve [1].

Two dimensions of the corpus are relatively well-covered: statistical rigor. Despite the parametric design of Marshall programs being well suited to factorial analysis, there were fewer than one in four (23%) studies that reported an analysis of variance or a regression model with interaction terms [20]. The material variability was also limited: the majority of programs had aggregate and binder batches that differed between replicate series which confounded the bitumen-content effect with material drift [11]. Mixes that fail specification windows are also an underrepresented element in the published record, so cannot be excluded by bias against favorable results: pooled optimum content is biased upwards. The funnel plot from the present meta-analysis was mildly asymmetric (Egger test, $p = 0.11$), and leave-one-out analysis indicated that two very finely graded studies drew the pooled estimate downward by $\sim 0.1\%$ [27], [28].

Finally, strength-based characterization dominates the corpus while performance-related properties are underrepresented. Very few parametric studies report moisture-conditioned stability, retained stability ratios or indirect tensile strength despite the fact that moisture susceptibility is the critical failure mode in tropical climates [29]. Variations of temperature susceptibility and ageing in the parametric sweep is nearly never conducted, although Lu and Isacsson indicate that aged binders tend to shift the optimal content [21]. Little validation under field condition: only few programs (see Table 1) compared plant-produced mix properties or pavement performance with laboratory-optimum contents [16], [14]. These gaps, together with the disaggregated reporting identified above, determine/define the research agenda: standardized parametric protocols, comprehensive volumetric reporting, factorial statistics analysis; and the association of laboratory optimum content in soils to field performance (14); the pooled benchmarks reported herein form reference values to which such protocols might be calibrated.

5. Discussion

Combined estimates show that the most suitable bitumen level of dense-graded Bituminous concrete using normal 60/70 or VG-30 binders is concentrated in a narrow band about five.2% by weight of mix with 95% confidence limits, i.e., five, four [27]. To practice this, it indicates that a design content from a Marshall parametric study is robust in the sense that $\pm 0.3\%$ construction tolerance (practically allowable in plant operations) would yield only 5–8% stability variation if the design is located around the flat region of slope curve [1], [2]. This soundness motivates the long history of using the Marshall method in specification [6]. The final selection should rather depend on the volumetric criteria, since the air-void and VFB windows are much narrower, as well as sensitive to bitumen content than a stability peak [15].

A comparison with other design frameworks is useful. This is because it uses the gyratory compactor and volumetric design at the design number of gyrations to furnish optimum binder contents that are generally 0.2–

0.4% lower than Marshall, even for equivalent materials gyratory compaction provides higher density at lower binder contents [20], [15]. This 5.2% systematic conservatism in binder quantity improves durability at the expense of low rutting resistance [8], so a slight OBC carried due to residual construction-based mirroring is desirable for Marshall-based mixtures. In terms of rutting, the Marshall-selected materials should be checked with a mechanism test such as repeated-load permanent deformation or the asphalt pavement analyzer [14], [30].

From the evidence reviewed emerges a number of procedural recommendations. One purpose is to keep the gradation in a narrow sub-band of the specification prior to bitumen sweep, and do so with specimens that are all taken from the same aggregate batch [7]. Second, a minimum of four specimens per bitumen level need to be tested full reporting of mean and range [12]. Third, the full volumetric set-air voids, VMA, and VFB-should be presented at each content because these quantities are what the decision is made upon [15]. Fourth, conditioning and compaction should strictly follow the standard protocols since deviations cause shifts in both stability and optimum content (11). Lastly, the chosen OBC should be retested against the 4% air-void criterion and, if deemed appropriate, against field cores taken from the trial section [1], [2]. Evidently, the testing on moisture susceptibility must be validated through stability or tensile strength retained before the production as a result of the parametric sweep was not able to show stripping potential alone [29], [12].

Limitations of this meta-analysis need to be considered. The sample size is limited (27 quantitative studies), the definition of dense-graded bituminous concrete was applied across multiple national gradation bands, data at the specimen/experimental level were aggregated without accessing any raw records, and statistical correction for scale effects was not possible. Publication bias cannot be ruled out (Egger test, $p = 0.11$) and the moderate heterogeneity suggests that the pooled values should be presented as central tendency estimates with credible ranges instead of fixed constants [28]. A standardized parametric test protocol would be the most valuable next step standardized gradation sub-band, compaction energy, conditioning and mandatory volumetric reporting across laboratories paired with open data repositories allowing specimen-level meta-analysis [3], [27].

6. Conclusion

This study has systematically reviewed and meta-analyzed five decades of laboratory studies on the parametric effect of bitumen content on the Marshall characteristics of dense-graded bituminous concrete. These classical trends the curved relationships between stability and unit weight (which rise to an optimum and fall thereafter) but not between flow and air voids (both of which rise monotonically, the latter falling monotonic) are confirmed by the quantitative synthesis, which places the pooled optimum bitumen content at 5.21% by weight of mix (95% CI: 5.02–5.40%, $I^2 = 64\%$) with conventional-binder sub-growing group at 5.13% content; modified-binder sub really intermediate-positioned at 0%;. The optimal content is a strong and slowly changing parameter, yet it is systematically influenced by gradation position, filler type, compaction effort and binder modification; these four covariates explained virtually all observed heterogeneity between studies. Most vulnerable methodological dimensions identified by critical appraisal were specimen replication, volumetric

reporting, conditioning protocol, and statistical analysis; the performance dimensions that have been least studied were moisture susceptibility, ageing and field validation. Standardized parametric protocols should be adopted for codes and practice (the R is 5.0–5.4% pooled range value synonymous with a first order target that designers can use for dense bituminous concrete-mix designs using traditional binders, that must prove volumetrically to the governing specification before production in-field). The penalty for not designing the binder sufficiently can be seen in the pooled stability improvement of ≈ 1.5 times at its optimum quantification, and the flow criterion eliminates over-design. Future work should build on the parametric framework towards performance tests moisture conditioning, rutting and fatigue and towards field correlation studies to link laboratory optimum to pavement performance over the service life [30], [14]

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