Concrete floors for warehousing and distribution facilities: fit for purpose?

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In warehouses and distribution centres the ground-floor slab is critical to the effective functioning of the facility, but there remains a considerable misunderstanding concerning the specification, design, and construction of this element of the works. Specifications are still often too onerous for appropriate cost-effective construction, or too vague, with conflicting requirements, resulting in unsatisfactory floor performance. There is no British Standard covering the design of ground-bearing slabs, and the structural design codes are not usually applicable to these floors. Although construction quality has shown some improvement in recent years with the advent of new techniques and materials, the floor is often still considered to be part of the 'groundworks', a notoriously low-skilled, highly competitive sector of the industry, and is procured accordingly. The new techniques themselves have resulted in some difficulties, with poor planning, and a lack of understanding of concrete behaviour usually being to blame. It is not surprising, therefore, to find that the majority of the enquiries to the Concrete Advisory Service concern floor slab problems. There is also often a perception that the slab is one of the most straightforward elements of any project. Hence, the overall attention paid to detail in design and construction is less than proportional to its ultimate importance to the efficient, and in certain cases safe, operation of the facility. This paper highlights the principal areas of consideration when specifying and designing warehouse floor slabs, identifies certain existing good and bad practices, and suggests the way forward to ensure that these floors are always constructed so as to be fit for purpose.

Floor slab function
Simply, a floor slab functions to distribute, without deformation or cracking, the loads applied to it to the weaker sub-grade below, in the case of a ground-bearing slab, or to the piles supporting it if designed as a suspended ground slab, and to provide a suitable wearing surface upon which the operations in the facility may be carried out efficiently and safely. Different specific properties are required by different industries, and even by competing operators in the same industry. One sector of industry that is particularly sensitive to the need for fit-for-purpose floor slabs is warehousing and distribution. Warehouse operators typically require that their floor slab should:

(a) be capable of supporting applied loads without cracking or deforming;
(b) have a minimum number of exposed joints;
(c) have maintenance-free joints that do not impede truck operating speeds;
(d) be dust-free (i.e. highly abrasion-resistant);
(e) have tolerances appropriate to the materials handling system to be used;
(f) be smooth and easy to clean, but not slippery;
(g) be flexible enough to accommodate possible future changes in operating systems;
(h) contribute to a safe, pleasant working environment.

Floor loading
2. The frequently quoted u.d.l. specifications are inadequate for the purpose of the structural design of ground-floor slabs. Such specifications are unrepresentative of the actual loading patterns to which slabs in warehouse facilities are subjected. Only in rare cases of block-stacking is the u.d.l. condition relevant, and even here the aisles are unloaded, thus the aisle width itself may become a more critical factor in the design.

3. Neal and Judge addressed this issue by defining non-dedicated warehouse floor loading in terms of four classes. Each of the proposed classes had typical critical loadings specified, depending on floor use. These are reproduced in Table 1. Specifying floor loading requirements in terms of a class which has a set of parameters associated with it is very useful as all parties can be confident (from a loading point of view) that the floor will be fit for purpose. Today, this classification remains the safest, most cost-effective, means of specifying speculative warehousing.

4. When warehouse floors are to be designed for a known set of loadings, the specification should include both the magnitude and distribution of the point loads, any restrictions to be placed on the proximity of joints in relation to these loads, and the...
frequency of any dynamic loads such as fork-lift truck movements.

**Structural design**

5. If a slab in a warehouse is to be durable then random cracks are to be eliminated, since under trafficking these will deteriorate, possibly ultimately rendering the surface unserviceable. Cracks result from tensile stresses exceeding the tensile capacity of the concrete. In ground slabs one of the causes of these stresses is slab flexure under load. In other flexural applications the high compressive strength of concrete is exploited and it is reinforced with steel to provide the necessary tensile strength. In order for this reinforcement to contribute to the load-carrying capacity of the composite section, the concrete in the tension zone has to crack. This is clearly not desirable in floor slabs. Non-suspended ground slabs should therefore be designed such that the flexural stresses generated under and around loads do not exceed a factored proportion of the tensile strength of the concrete.

**Ground-bearing slabs**

6. For many years it has been accepted that the work of Westergaard provides a sound basis for ground-slab design.\(^2\) His original theoretical work has been modified by experiment, and all of this was brought together in the authoritative Cement and Concrete Association report, published in June 1982.\(^3\) In 1988 a more concise B.C.A. document developed these design principles further, following detailed research into the basic parameters determining loading types and the material characteristics of both the concrete and sub-grade.\(^4\) This latter document contains useful general load tables, and effective guidance on assessment and enhancement of the modulus of sub-grade reaction to use in the slab design. The influence of the sub-grade on ground-bearing slab design is taken as that of an elastic medium. Tensile stresses induced in the slab by point loads are, however, quite insensitive to variations in the modulus of sub-grade reaction (see Table 2).

7. CBR test results alone should be considered too unreliable for slab design, as they reflect only a comparatively shallow stress bulb, and hence do not indicate to what extent the sub-grade is stressed at depth. An adequately defined site investigation is therefore necessary, particularly in the case of high-bay warehouses with materials handling systems sensitive to floor tolerances which can be disturbed by even very small degrees of consolidation. Further, as loadings have increased, some ground-bearing slabs located on plastic soils, designed in accordance with the recognized documents, but based on inadequate soils information, have suffered tensile cracking longitudinally in the aisles as a result of differential consolidation between these unloaded areas and the heavily loaded sections beneath the racks. There is no authoritative guidance to this design problem at this time, although computer studies currently being undertaken by F. R. Neal in collaboration with South Bank University are expected to yield appropriate solutions.

8. Where consolidation of plastic soils is determined to be a potential problem following an assessment of the S.I. and the actual loading pattern anticipated, a suspended slab is the only effective solution. However, where the ground can be improved using techniques such as vibro-replacement or dynamic compaction, and an adequate granular sub-base is provided, the slab may be considered to be ground-bearing and designed in accordance

### Table 1. Load classes and typical maximum critical loadings

<table>
<thead>
<tr>
<th>Load class</th>
<th>Floor area usage</th>
<th>Typical maximum critical loadings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Pallet racking</td>
<td>Four levels (one on floor) 0.75 t unit loads. (4.5 t end frame)</td>
</tr>
<tr>
<td></td>
<td>Shelving</td>
<td>End frame of 4 t</td>
</tr>
<tr>
<td></td>
<td>Mezzanine floor</td>
<td>Design load 3.5 kN/m²</td>
</tr>
<tr>
<td></td>
<td>Fork lift</td>
<td>Capacity 2.0 t</td>
</tr>
<tr>
<td>Medium</td>
<td>Pallet racking</td>
<td>Four levels (one on floor) 1.0 t unit loads (6.0 t end frame)</td>
</tr>
<tr>
<td></td>
<td>Shelving</td>
<td>End frame of 5.4 t</td>
</tr>
<tr>
<td></td>
<td>Mezzanine floor</td>
<td>Design load 5.0 kN/m²</td>
</tr>
<tr>
<td></td>
<td>Fork lift</td>
<td>Capacity 3.0 t</td>
</tr>
<tr>
<td>Heavy</td>
<td>Pallet racking</td>
<td>Four levels (one on floor) 1.5 t unit loads or six levels (one on floor) 1.0 t unit loads (10 t end frame)</td>
</tr>
<tr>
<td></td>
<td>Shelving</td>
<td>Unlikely to be applicable</td>
</tr>
<tr>
<td></td>
<td>Mezzanine floor</td>
<td>Design load 7.25 kN/m²</td>
</tr>
<tr>
<td></td>
<td>Fork lift</td>
<td>Unlikely to be critical</td>
</tr>
<tr>
<td>Very heavy</td>
<td>Pallet racking</td>
<td>Five levels (one on floor) 1.5 t unit loads or seven levels (one on floor) 1 t unit loads (12 t end frame)</td>
</tr>
<tr>
<td></td>
<td>Shelving</td>
<td>Unlikely to be applicable</td>
</tr>
<tr>
<td></td>
<td>Mezzanine floor</td>
<td>Design load 9.5 kN/m²</td>
</tr>
<tr>
<td></td>
<td>Fork lift</td>
<td>Unlikely to be critical</td>
</tr>
</tbody>
</table>

### Table 2. Variation of slab thickness with modulus of sub-grade reaction (K) heavy load class*

<table>
<thead>
<tr>
<th>Sub-grade classification</th>
<th>Typical modulus of sub-grade reaction K: MN/m³</th>
<th>Slab thickness: mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very poor</td>
<td>13</td>
<td>235</td>
</tr>
<tr>
<td>Poor</td>
<td>27</td>
<td>230</td>
</tr>
<tr>
<td>Good</td>
<td>54</td>
<td>225</td>
</tr>
<tr>
<td>Enhanced</td>
<td>82</td>
<td>220</td>
</tr>
</tbody>
</table>

* Based on characteristic concrete strength of 40 N/mm².
with the previously described principles and documents.

9. Ground-floor slabs are still found with fabric specified in the top and bottom. This is fundamentally wrong, unless the slab has been designed as suspended between piles or beams. The practice of incorporating relatively light fabric to 'span any soft spots' is not consistent with any recognized method of design, and the moment of resistance of such a section is in any case likely to be less than an unreinforced one of the same depth.

**Suspended ground-floor slabs**

10. Suspended slabs are usually designed as flat slabs, and occasionally as simply supported between ground beams. The latter solution is preferred. This allows for stress relief joints to be detailed over the beams, and by constructing the beam–slab interface so that no connection occurs there is no inhibition to free movement of the slab. As a result, there is significantly less risk of random shrinkage cracking occurring than with flat slab design where considerable restraint is imparted into the slab by the piles or 'drops'. Structurally the beams can also double as portal ties.

11. Some designers consider flat slabs to be more economic. For simplicity, flat slabs are usually designed based on a u.d.l., which, as shown, does not reflect the true loading pattern, and unexpectedly severe cracking sometimes occurs. To help prevent this, steel must be provided continuously in the top of the slab, and should be detailed to control crack width, as suggested by Simpson, with several small diameter bars at close centres being preferred to a lesser number of larger diameter bars at wider spacings. Problems can also occur as a result of plastic settlement where inadequate cover to the top steel is specified, particularly if the settlement is of a differential nature where 'drops' are detailed. Not only can cracking result, but also difficulties are encountered in finishing these slabs to tight tolerances. A minimum of 40 mm cover is required; 50 mm is preferred by most floor layers. Wire guidance systems are often specified in high-bay warehouse facilities, and in these instances a greater cover may be required. Currently, few suspended ground slabs are designed and detailed as described above, and problems with unacceptable cracks and finishing problems continue to occur. There is a need for a definitive design guide for these slabs.

12. Post-tensioned slabs provide an excellent technical solution for both suspended and ground-bearing slabs. In ground-bearing post-tensioned slabs, random shrinkage cracks can be eliminated, and thinner slabs can result from the elimination of critical corner and edge loading conditions. Similar benefits apply to suspended ground slabs, and here post-tensioned slabs are often much simpler to construct and are frequently shown to be more economic than 'traditional' reinforced concrete design. Post-tensioned slabs have been successfully constructed worldwide for many years, and the design is relatively straightforward. It is unclear why wider use is not made of the technique in the UK.

**Fibre-reinforced slabs**

13. The second edition of Concrete Society Technical Report 34, published in 1994, describes the main properties of fibres used in concrete floor slabs. From a design point of view, the concepts of 'toughness' and 'equivalent flexural strength' are introduced for steel fibre concrete slabs. This toughness, or ductility, can improve the load-bearing capacity of floors considerably when compared to plain concrete. Research already carried out in the UK has indicated that very significant savings in slab thickness can be achieved. However, to date, these tests have been on relatively small-sized panels, and the modes of failure recorded have not reproduced those that occur in actual slabs under service loads. Some steel fibre manufacturers offer warranted designs, but these tend to be conservative when compared to the theoretical results from the test work. No recognized UK design guides exist at present for these slabs. As with post-tensioning, there is an 'on-cost' when compared to a plain concrete slab, but again an established track record in other countries exists, and these floor slabs are particularly suited to modern large-pour construction techniques. Steel fibre concrete slabs cannot be designed as suspended floors.

14. Polypropylene fibres do not contribute to the load carrying capacity of slabs. The use of glass fibre reinforcement in ground-floor slabs is in its infancy, but this promising development may combine the benefits of polypropylene fibres evident during the plastic concrete state with increased slab flexural capacity.

**Portal ties**

15. When designing slabs it is still common practice to tie the slab into the portal frame in order to accommodate the horizontal thrust from the legs. This is to be discouraged, and separate ties under the slab designed, as recommended by Deacon. Since ground-bearing slabs fail under flexure, it is clear that any additional tensile stress will reduce the concrete's ability to withstand the loads applied to it. By good fortune, the designers' details and site practice do not always result in fully tying the portal frame,
and induced stresses tend to be significant only at the perimeter of the slab, where it is usually relatively lightly loaded. However, even in these instances, cracking often occurs as a result of the ties restraining the natural drying shrinkage of the concrete.

**Floor joints**

16. It is widely acknowledged that joints provide the greatest source of problems in industrial floors, including warehouses. Careful planning of joint location and clean detailing are essential to minimize the risk of damage to the potentially vulnerable edges of these, particularly in respect of construction joints. Publications by Deacon, the Concrete Society, and others illustrate typical joint details, and many floor constructors and specialist suppliers promote their own solutions. However, few, if any, of the details given are appropriate for all situations, and it is important to understand what the intended purpose of each particular type of joint is.

17. Joints are provided in ground-bearing slabs for two principal reasons: first, as construction joints, the number and location of which are related to the method adopted and to the tolerances specified; and second, for the purpose of limiting tensile stresses in the concrete resulting from thermal and drying shrinkage movements and hence to eliminate random cracking, collectively known as 'control joints'. It has been accepted for many years that expansion joints are not required in slabs on ground constructed within a weathered building envelope.

18. For suspended slabs not designed as simply supported, the Concrete Advisory Service advocates the pouring of these in sections as large as practical. Control joints are not applicable, and shrinkage crack control is achieved by appropriate reinforcement design and detailing. Joints in simply supported suspended slabs may be detailed as if ground-bearing, subject to construction or control joints perpendicular to the direction of span being located directly over the support beams, and the reinforcement detailed accordingly.

**Construction joints**

19. Ideally, construction joints should be eliminated altogether wherever possible. Provided that tolerances are not too onerous, areas up to 4000 m², or more, can be poured continuously in one day using large-pour construction techniques. Clearly, this enables many facilities to be installed free of construction joints, and dramatically reduces the numbers required in many others. With a minimum of construction joints it is much easier to detail these in low-traffic areas or, if this is not possible, to allow for incorporating high-performance details without contributing significantly to the overall cost of the floor.

20. In warehouse floors with onerous tolerances, which, in order to meet these requirements, require more frequent joints, the longitudinal construction joints should be located beneath the racking system, the ideal location for these joints being mid-way points between the front and back legs of the racks, with the transverse joints located at the mid-points of the racking entry bays. This not only ensures that the vast majority of the most troublesome construction joints are not subject to traffic, but may also allow for a more economical structural design, through the elimination of critical corner point load conditions. Consideration should always be given to specifying a large-pour floor in the 'free movement' areas outside of the racked area.

21. Particular care with both workmanship and detailing should be exercised at 'free joints', i.e. where the dowels are debonded. By design, these joints will open up over time, and, particularly in the case of large-pour floors where the spacing may be very large, the final width can be considerable. Some documents recommend the incorporation of a sealing groove at the time of construction. This can be very difficult to form, and tends to be covered in 'laiture'. Joints formed using very straight square-edged formwork, sawn 3 mm wide after some of the initial movement has taken place, have proved more successful. For large-pour floors the use of steel angle reinforcement at these free joint edges is highly desirable, and is essential at perimeter doorways subject to fork-lift truck traffic. Provided that care is taken to ensure adequate anchorage and that the angles do not twist or rotate during concrete placement, these provide an excellent detail. As a good practice, this detail should be adopted in all trafficked perimeter locations, whatever the method of construction.

22. Tied construction joints, as the name implies, should not open up. In large-pour systems they should be located mid-way between sawn joints installed at their usual spacing. Where a mix of tied and free joints is used, as is often the case with 'traditional' long-strip construction, clearly it makes sense to adjust the joint layout to try to ensure that only tied joints occur in the heaviest trafficked areas.

23. Some manufacturers promote the use of precast concrete rails for use as permanent formwork in place of timber or steel. There is no British standard covering their design or performance. Good workmanship is even more critical when using these, and the specifier must ensure that they are installed precisely in accordance with the manufacturer's instructions. Despite improvements being made
continuously, there is evidence to suggest that these rails may still be unreliable if used in warehouse slabs subject to very heavy traffic.

24. Specifiers should beware of clients claiming to require a change of layout in the future. This rarely happens, and as the technology of materials handling equipment continuously changes, the exact future requirement is impossible to predict accurately. If joints are located 'for the future', but break down after six months, the facility will be disrupted and the future becomes even more uncertain. It is essential that the floor works on day one; only then will it be considered fit for purpose.

Control joints

25. Control (or contraction) joints should preferably be formed by saw-cutting with a diamond-tipped blade within 24 hours of concrete placement. The use of plastic inserts, or similar methods of forming grooves in the wet concrete, should be discouraged in warehouse floors, because the insertion of these involves disturbing the surface, and consequently creates unnecessary difficulties in obtaining fine tolerances. Further, saw-cutting at the appropriate time provides a much neater joint. Although the initial cost of saw-cutting is higher, particularly in areas of flint or similar hard aggregates, the long-term costs of disruption in the event of joint breakdown of a poorly inserted strip are clearly many times the initial additional outlay. Under no circumstances should top and bottom crack inducers be specified. There is no guarantee that these will align vertically, and in all probability a crack propagating from the bottom inducer will occur close to, but not coinciding with, the top one.

26. Saw-cutting must itself be carefully timed. This must not commence too early or a ragged joint will occur that will break down easily under traffic. If it is left too late, the stresses resulting from thermal shrinkage will cause cracks to occur ahead of the cutting. It is also important to commence saw-cutting at locations of maximum stress, such as internal corners.

27. The spacings of contraction joints in traditional construction are given in the standard references. In an unreinforced slab, uncontrolled cracks occur at a spacing at which the tensile stresses resulting from restraint of the natural shrinkage movement of the slab exceed the tensile capacity of the concrete. The location of sawn joints should be determined accordingly. In respect of long-term drying shrinkage, due account should also be taken of the loads imposed upon the slabs (from the point of view both of induced flexural stresses, and of the increase in frictional forces) and other external restraints, such as portal ties.

Isolation joints

28. The slab should be isolated from the main structure and any other intrusions through or partially into it. Failure adequately to isolate the floor will cause a considerable increase in local stresses in the concrete, in most cases resulting in the occurrence of shrinkage cracks.

29. Diamond-shaped column surrounds result in unnecessarily large 'infill', and it is often difficult to align formwork and saw-cuts to the points of these. Unless it is necessary to encase steelwork independently of the slab for other reasons, it is preferable to use the detail shown in Fig. 1. This detail is particularly suitable where onerous tolerances or coloured finishes have been specified. Corners of square intrusions should always be trimmed with a minimum of two T10 bars 900 mm long. Circular column surrounds eliminate the requirement for these bars, but as they take up a larger area of the floor slab they may become subject to traffic, with the resultant implications for maintenance of the joints.

30. The isolation joint material should be glued to the intrusion, with joints taped, must be sufficiently compressible, and is usually manufactured from expanded polyethylene. ‘Compressible boards’ are not suitable for effective isolation, particularly with large-pour floors.

Joint sealing

31. The sealing of joints subject to warehouse traffic needs to be done with a material that will provide support to the edges of the joints. Unfortunately, most of the materials that have this property also have a very low strain capacity. Therefore sealing should be left as late as possible to enable much of the drying shrinkage to have taken place. However, modern fast-track programmes often allow only a few weeks between laying of the slab and handover to client, insufficient for any significant drying shrinkage to have taken place in a well-cured slab. If the joints are sealed at this time it is likely that resealing will

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**Fig. 1 Typical isolation detail at internal column**
be required at a later date. If they are left unsealed all but the narrowest of joints may suffer damage, thus requiring some repairs before sealing after a period of 12 months or so. The use of flexible sealants in narrow joints subject to fork-lift traffic is not cost-effective. These provide little arris support and are often ‘plucked out’ by the rubber tyres of the trucks. Clients need to be educated in the need for the two-stage ‘hard’ sealing process, clearly only the aisles and free-movement areas of warehouses needing to be resealed, at, for example, the end of the defects liability period.

32. Due account must be taken of the proposed traffic by the specifier at the time of slab design. For example, if small steel wheels are to be used in the facility even narrow, well-formed and sealed joints will suffer degradation over time. Either the client should be persuaded to change the tyre material, or a jointless floor slab will need to be specified. Various alternative solutions for ‘jointless floors’ are now available, including the use of shrinkage compensating cement and steel fibres. The preferred solution for most circumstances is post-tensioning, because, subject to certain restrictions in tension lengths, the construction joints are also tightly closed by the process, and there is a greater predictability of slab performance.

Tolerances

33. If joints cause the greatest practical problems in ground-floor slabs, then tolerances undoubtedly cause the greatest number of arguments and disputes. These either result from an ill-defined specification, poor workmanship, unsuitable materials and laying conditions, differing interpretation of survey results, inaccurate or non-representative surveys, a combination of all of these, or a total misunderstanding of the clients’ requirements in the first place.

34. Where there are no racks, or no indication is given of the materials handling system to be used, tolerances should be specified that allow some form of large-pour system to be adopted, with a view to eliminating as many construction joints as possible. Floors to speculative warehouse developments should not therefore be specified to flatness tolerances that demand narrow strip construction. The alternative is a floor with a large number of potentially troublesome joints, which in all probability will remain exposed for all of the slab’s working life, and with the tolerances at these joints almost certainly outside the specification. Also, at the time of construction of the slabs to such buildings traffic paths, by definition, are not known. In order to achieve and measure the most onerous tolerances, the wheel track path of the fork-lift trucks etc. must be known before floor laying begins.

35. An attempt has been made in Technical Report 34 to address the most fundamental of the issues, namely that of producing a specification that is acceptable to the materials handling equipment suppliers, is clear and unambiguous, is achievable in practice, and can be measured relatively straightforwardly. However, disputes continue. Despite improved clarity in the second edition of this document, specifiers still select inappropriate tolerances, and choose particular criteria from various sections of the categorised tolerances. Table 7.1 of Technical Report 34, reproduced here as Table 3, should be used as it is written; if this is done, warehouse floor slabs specified and constructed – and checked for compliance – in accordance with the tolerances shown will be fit for the purpose described.

36. The free movement area tolerances of Technical Report 34, second edition, have caused some controversy among floor-laying contractors. However, there is a need for short-wavelength tolerances to be controlled in such areas, and this ‘flatness’ is no more

<table>
<thead>
<tr>
<th>Category</th>
<th>Location</th>
<th>Property I</th>
<th>Property II</th>
<th>Property III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superflat (SF)</td>
<td>VNA warehouses with minimum clearance</td>
<td>Difference in elevation over 300 mm along wheel tracks</td>
<td>Difference in slope over 600 mm along wheel tracks</td>
<td>Difference in elevation across wheel track</td>
</tr>
<tr>
<td>Category 1</td>
<td>VNA warehouses with racking height of 8–13 m</td>
<td>Two figures are quoted in Table 7.1. The first gives a value which not more than 5% of readings are permitted to exceed. None of the measurements are to exceed the second value given. Both property limits need to be complied with for the floor to be considered satisfactory. Both tracks are to be measured. Remedial action is usually by grinding</td>
<td>Two limits are quoted as for properties I and II, with different values for wheel tracks up to 1.5 m and those above 1.5 m</td>
<td></td>
</tr>
</tbody>
</table>
difficult to achieve than the 3 m grid tolerance specified in the first edition of the document. It can be achieved by large-pour techniques, but some relaxation in the 3 m grid tolerance could be appropriate in future revisions to the document, as this tends to be less critical provided that short-wavelength and overall level requirements are met. Also, the 3 m grid tolerance itself is a recipe for dispute. For example, if the random 3 m grid fails to pick up an area clearly out of tolerance, should the grid then moved to ensure that it covers this area (and in all probability miss another)? How are out-of-tolerance areas rectified? Is some type of contour plan to be used to determine the extent of remedial work? Materials handling equipment suppliers should be consulted before the tolerance specification is decided upon, and before work starts on site complete clarity needs to be established on how the floor is to be measured, by whom, and what is to be done if areas are found to be out of tolerance. A reasoned judgement should always be made by an informed specialist in the event of any dispute.

37. Other disputes centre around measurements with respect to a straight edge laid on the floor. Part 2 of BS 8204 incorporates such a specification.10 Table 1 of this document also refers to three classes of floor as 'utility', 'normal' and 'high'. Owners do not feel comfortable with a utility floor, even if it is perfectly adequate for their needs, when in all other respects they have commissioned their design team to provide them with a 'high'-quality facility. The 'normal' standard is anything but, with very few floor slabs in the UK meeting this standard throughout the whole of the floor. BS 8204 does not define frequency of measurement, or how areas should be selected for test for compliance. Neither does it provide guidance on what measures should be taken to rectify out-of-tolerance areas. To measure a floor slab in accordance with a straight-edge tolerance is time-consuming and costly, and rarely actually done. Also, BS 8204 itself recognizes that this method of specifying surface regularity does not take into account the 'waviness' of the floor; hence it is not surprising that Barnbrook11 and others do not support the use of these tolerances for warehouse floors.

38. In the United States the F number system is commonly used. A document issued by the American Society for Testing and Materials describes in some detail the number and location of readings, how to undertake measurements, methods for rectification and so on.12 While the adoption of this standard in the UK is not advocated, a similar BSI document incorporating much of Technical Report 34, but removing once and for all any straight-edge tolerances, would be a major contribution to eliminating much of the conflict in this area of floor construction.

39. Education is still needed to prevent overspecification of slabs. It is just not possible to construct floors to Technical Report 34 category 1 or superflat tolerances in all directions. Clients cannot have such an onerous tolerance and flexibility. If the floor is constructed initially to these tolerances, it will not be within tolerance if the aisles are rotated through 90° from that defined at the time of construction, neither will it have been measured outside of the predetermined paths of truck travel, and it will almost certainly not be within tolerance adjacent to the joints. Therefore, even a lateral movement of the racking system will require another survey and some grinding work. Further, over time the construction joints will probably curl even more out of tolerance. As with the selection of joint locations in the slab, floor tolerances should be specified for the materials handling system and racking system proposed at the time of commissioning of the facility, with the method of construction and finishing techniques specified so as to give the maximum flexibility of operation in the future.

40. Warehouse floor slabs should always be checked for compliance as work proceeds. Electronic floor measurement devices are now available from a number of specialist floor-survey companies to simplify this essential procedure.

Wearing surface performance

41. In addition to cracking, poor joint performance and inappropriate tolerances, some floor slabs fail to meet the expectations of the client in terms of either abrasion resistance, appearance, or ease of cleaning.

42. High abrasion resistance is important to eliminate wear of the slab surface. This wear leads to dust in the atmosphere (and the consequential contamination of products), and in severe cases to disruption of the materials handling system.

43. Abrasion resistance of concrete floor slabs is influenced by many factors. Extensive research work has been undertaken at Aston University by Kettle and Sadegzadeh,13-15 both into the various influencing factors, and developing a reliable method of testing for this property, and this has also been supported by Chaplin's work.16 A class system for abrasion resistance was first defined in Part 2 of BS 8204.17 BS 8204 gives only limited guidance to the specifier, particularly as the concrete mixes specified for the various classes are often uneconomic, and unsuitable for use with modern construction methods. The adoption of 'wear-in' values in Technical Report 34 for the various classes of floor described in BS 8204 is therefore of significant importance. This allows
for in situ abrasion resistance to be measured using the portable accelerated abrasion testing apparatus. Developed jointly by Aston University and the Cement and Concrete Association, this apparatus measures the wearing of the surface under steel wheels.

44. To specify concrete strength and a ‘power floated finish’ does not adequately define the performance of the wearing surface. A well-finished, well-cured 40 N/mm² concrete can provide abrasion resistance equivalent to BS 8204 class AR2 or better, but equally, with less care a soft, dusty finish could also occur. The abrasion resistance of a warehouse floor should therefore be specified in the form of a ‘wear-in’ value, depending upon the nature and frequency of the traffic (Table 4).17

45. ‘Dry-shake’ toppings provide a cost-effective solution to achieving high abrasion resistance. They permit the use of a relatively low-strength base concrete (usually in the range of 30–40 N/mm²) with economic cement contents, to provide the required structural performance, and result in a very dense, high-strength monolithic wearing course when applied correctly. Dry-shake finishes should only be applied by specialist contractors, and modern developments allow for machine application only to be specified, thereby ensuring an accurate spread rate. This enhances uniformity of finish, and enables the floors to be finished to a higher standard of flatness than was the case with traditional ‘broadcast’ methods.

46. Suitable finishing specifications and good finishing techniques result in high abrasion resistance of the floor surface and ensure a smooth, highly reflective finish. Reflectivity, a function of surface density and the quality of the final trowelling operation, not only helps to provide an environment that is pleasing to the facility’s employees (particularly where coloured dry-shakes are used) but also offers real savings in terms of reduced lighting costs and enhanced productivity. Similarly, a smooth surface, free of defects, is easier to clean (and hence reduces costs), and enhances the corporate image of the warehouse operator. This can be of surprising importance, particularly in the case of third-party contract distributors, and accounts for the frequent requirement for monolithic coloured topping in such facilities.

Conclusions
47. Only by providing the right combination of load-carrying ability, freedom from cracks, appropriate tolerances, and wearing surface performance will a warehouse floor allow the operations to be carried out upon it to be done with maximum efficiency and cost-effectiveness. Any defect in specification or workmanship will be magnified by the constant, demanding traffic found almost uniquely in these environments. In many cases current practice does not offer the best chance of achieving the desired result. In the short term, greater use should be made of specialist expertise in the design and specification process. In the longer term, a comprehensive review of the most relevant British standard, BS 8204, and equivalent European standards, would provide the most appropriate route to elevating the importance of the correct design and construction of the floor slab to a level equivalent to the economic consequences of its failure to be fit for purpose.

Table 4. Wear-in values applicable for BS 8204 (Part 2) classes of floor slabs

<table>
<thead>
<tr>
<th>BS 8204 class</th>
<th>Duty</th>
<th>Application</th>
<th>Maximum depth of wear: mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special</td>
<td>Severe abrasion and impact</td>
<td>Very heavy-duty engineering workshops etc.</td>
<td>0.05</td>
</tr>
<tr>
<td>AR1</td>
<td>Very high abrasion steel wheel traffic and impact</td>
<td>Heavy-duty industrial workshops, special commercial, etc.</td>
<td>0.1</td>
</tr>
<tr>
<td>AR2</td>
<td>High abrasion steel or hard plastic wheel traffic</td>
<td>Medium-duty industrial and commercial</td>
<td>0.2</td>
</tr>
<tr>
<td>AR3</td>
<td>Moderate abrasion rubber tyre traffic</td>
<td>Light-duty industrial and commercial</td>
<td>0.4</td>
</tr>
</tbody>
</table>

References
5. Simpson D. Design of suspended slabs on ground. Concrete Society, Slough, Concrete Advisory Service Data Sheet No. 5, August 1993.