TECHNOLOGICAL ASSESSMENT OF CEMENT MATRIX DETERIORATION IN CONCRETE FLOORINGS OF CATTLE BUILDINGS UNDER MANURE EXPOSURE: A REVIEW

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ABSTRACT

Concrete floorings in cattle buildings are operated in an environment where the load - bearing capacity of the material is related not only to compressive strength but also to the resistance of the cement matrix to manure, urine, moisture, organic acids, sulfate compounds, microbiological activity and mechanical abrasion. In this review, a technological assessment of the main mechanisms of concrete deterioration under contact with an aggressive livestock environment is provided and the requirements for suitable concrete and cement systems are summarized. Publications, standards and applied studies related to concrete floors, cement matrix, organic acids, sulfate attack, calcium leaching, microbiologically induced corrosion and innovative binder systems were analysed. The data show that concrete durability in a livestock environment should be assessed through a set of indicators: compressive strength, water absorption, density, porosity, permeability, sulfate resistance, acid resistance, wear resistance and reinforcement protection. From a technological point of view, concretes with a low water - cement ratio, a dense structure, adequate compaction and curing, as well as sulfate - resistant, slag, pozzolanic or alkali - activated binder systems, are considered the most justified. The main limitation in the literature remains the lack of long - term field studies in real cattle buildings where chemical, biological and mechanical factors act simultaneously.

Keywords: cement matrix, concrete deterioration, cattle buildings, manure exposure, sulfate attack, organic acids, permeability, technological assessment.

INTRODUCTION

Concrete is used as a basic material for floorings, manure alleys, channels and other structural elements in cattle buildings. In these facilities the concrete flooring is assigned a dual function: a structural function, because mechanical loads are carried, and a technological function, because hygiene, traction, cleanability and safe animal movement are determined by the floor surface. Therefore, concrete selection should not be based only on compressive strength. The operating environment and the transport properties of the material should also be considered [1 - 5].

In livestock buildings concrete is exposed for a prolonged period to manure, urine, washing water, ammonia, hydrogen sulfide, organic acids, sulfates, biofilms and abrasion. This environment is more variable than standard laboratory acidic or sulfate solutions because chemical, biological and physico - mechanical actions are included at the same time. For this reason, deterioration of the cement matrix should be regarded as an integrated process rather than as the separate action of one aggressive agent [6 - 9].

The aim of the present article is to systematize and critically assess the technological evidence for concrete alteration under contact with manure and related aggressive factors. Emphasis is placed on specific concrete properties, suitable types of concrete and cement, innovative binder systems and the limitations that arise when laboratory results are transferred to real cattle buildings.

LITERATURE REVIEW

The present study was developed as a technological and scientific literature review. The analysed sources were grouped into six directions: floorings and operating environment in livestock buildings [1 - 9], composition and properties of concrete and the cement matrix [10 - 25], composition and emissions from manure [26 - 43], mechanisms of microbiological, acid, sulfate and calcium deterioration [44 - 64], mechanical abrasion and corrosion manifestations in farm environments [65 - 75] and innovative binder systems including alkali - activated materials, geopolymers, graphene oxide and cattle manure ash [76 - 85].

CONCRETE AND CEMENT MATRIX AS TECHNOLOGICAL SYSTEM

Concrete is considered a multicomponent system composed of cement, water, fine aggregate and coarse aggregate and, when required, chemical and mineral admixtures. This system is shown in Fig. 1, and it forms the basis on which the properties of flooring in livestock buildings are developed [10, 11].

According to BDS EN 206:2013+A2:2021/ NA:2021, the following main types of concrete are distinguished and presented in Table 1.

The structure of the matrix is presented in Fig. 2. Special importance is assigned to the C - S - H phase, calcium hydroxide and capillary pores. The matrix is the most sensitive part of concrete during contact with aggressive liquids. Its durability is determined by hydration products, capillary porosity, the transition zone between cement paste and aggregates and the degree of pore connectivity [22].

The type of cement used is also of essential importance. Table 2 systematizes cement mixtures that can be used in the design of concrete floorings for an aggressive livestock environment.

FLOOR STRUCTURE AND MANURE EXPOSURE

A conventional concrete floor in a cattle building includes a compacted base, a concrete layer and a surface layer or screed. This multilayer structure is shown in Fig. 3. Under real conditions, the surface layer is most strongly exposed to manure, urine, water, cleaning, hoof loading and abrasion [7, 16, 24, 25].

To limit the retention of aggressive liquids on the surface, the technological requirements for the flooring should be considered as a system. Table 3 presents minimum practical parameters for floors in cattle buildings.

AGGRESSIVE MANURE ENVIRONMENT AND MAIN DETERIORATION MECHANISMS

Cattle manure contains a high amount of water, organic matter, nitrogen compounds, sulfates, mineral

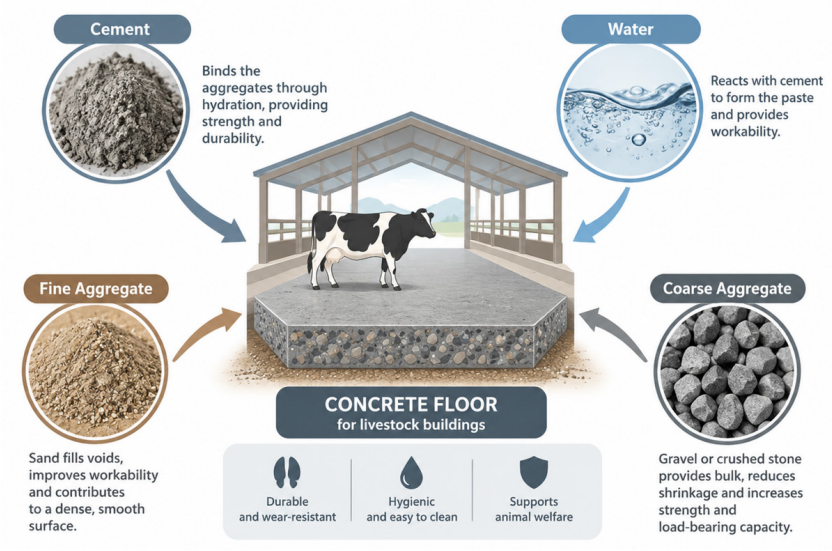


Fig. 1. Main components of concrete and their functional roles [10, 11].

Table 1. Types of concrete according to their technological characteristics [20].

Classification criterion	Concrete type / designation	Brief technological characteristic	Significance for floorings in cattle buildings
By density	Normal - weight concrete, C	Concrete with normal density, most commonly used in structural construction.	Basic material for floors, foundations, channels, walls and other elements in livestock buildings.
By density	Lightweight concrete, LC	Concrete with reduced density obtained through lightweight aggregates.	Limited applicability for floorings because lower wear resistance and higher porosity are usually observed.
By production method	Ready - mixed concrete / site - mixed concrete	Concrete mixture produced in a batching plant or directly on the construction site.	Ready - mixed concrete provides better control of composition, water - cement ratio and uniformity.
By compaction method	Compacted concrete / self - compacting concrete, SCC	Compaction reduces air voids and improves the concrete structure.	Good compaction is mandatory for limiting the penetration of urine, manure liquid, sulfates and organic acids.
By compressive strength	C fck,cyl/ fck,cube; LC fck,cyl/fck,cube	The strength class is determined by characteristic cylindrical and cube strength, e.g. C20/25.	For floorings in an aggressive livestock environment, higher classes combined with low w/c and good durability are recommended.
By consistency	S, F, V, C	Workability and the ability of the concrete mixture to be placed and compacted are indicated.	Suitable consistency ensures good filling, reduced porosity and higher resistance to the penetration of aggressive liquids.
By environmental exposure	X0, XC, XD, XS, XF, XA	The classes account for the risk of corrosion, freeze - thaw action and chemical aggression.	For livestock buildings, the classes related to moisture, chemical action, freezing and reinforcement protection are especially important.

components and organic acids. This composition creates conditions for chemical dissolution, decalcification, microbiological action and an increase in moisture in the surface zone of concrete [26 - 37]. These components and their possible technological significance for concrete are summarized in Table 4.

Biochemical decomposition of manure occurs in liquid and gas phases. The schematic representation in Fig. 4 summarizes the liquid phase, where urea hydrolysis and organic matter decomposition occur, and the gas phase, where CO_2, NH_3 and CH_4 are released [42, 43].

Dissolved ions, ammonium nitrogen and organic products are formed in the liquid phase and the chemical activity of the environment is maintained by them. In the gas phase, NH_3, CO_2 and CH_4 are released. CO_2 participates in the acid - base equilibrium and NH_3 is related to ammonium transformations and nitrogen losses. In the presence of moisture, biofilms and sulfur compounds, similar processes may create local conditions for acid and sulfate attack on the cement matrix [42 - 45].

The main deterioration mechanisms are acid attack, sulfate and sulfuric acid attack, microbiologically induced corrosion, calcium leaching, increased porosity and mechanical abrasion. Under real operating conditions these processes act simultaneously and reinforce each other: the protective surface layer is

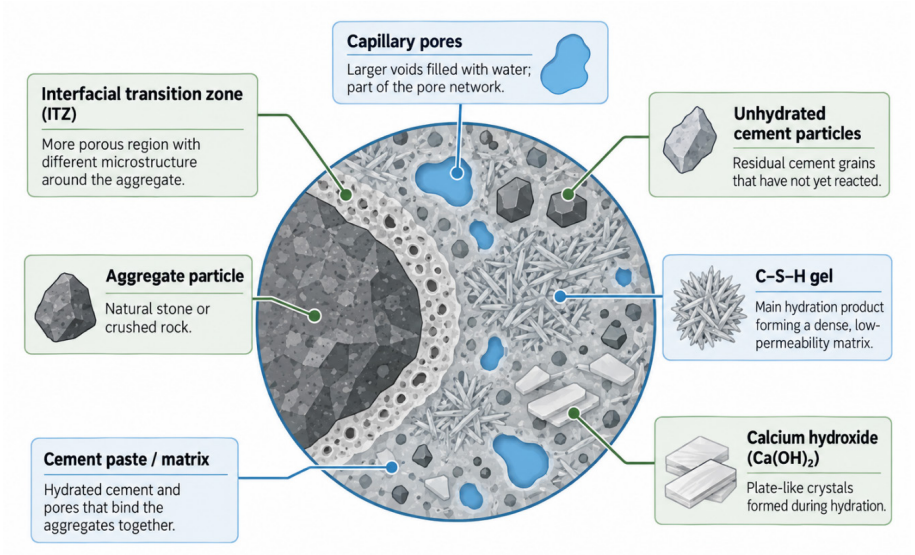


Fig. 2. Schematic representation of the cement matrix structure in concrete [22].

Table 2. Cement types and applicability for concrete floorings in an aggressive livestock environment.

Cement type	Main characteristic	Assessment for cattle buildings
CEM I	High clinker and calcium hydroxide content.	Suitable only when good protection, low w/c and limited aggressiveness are provided.
CEM I - SR	Low C_3A content and increased sulfate resistance.	Suitable in the presence of sulfates, urine and risk of gypsum and ettringite formation.
CEM II/A - S or CEM II/B - S	Portland slag cement.	Suitable for a denser matrix and reduced permeability.
CEM III/A or CEM III/B	Blast - furnace slag cement with a high slag content.	Promising under chemical aggressiveness, but curing and early strength must be controlled.
CEM IV and CEM V	Pozzolanic and composite cements.	Suitable when resistance to acids, sulfates and abrasion is technologically verified.

**CEM - common cement type; SR - sulfate resistant. Source: compiled according to BDS EN 197 - 1 and durability - oriented cement literature [18, 23, 24].*

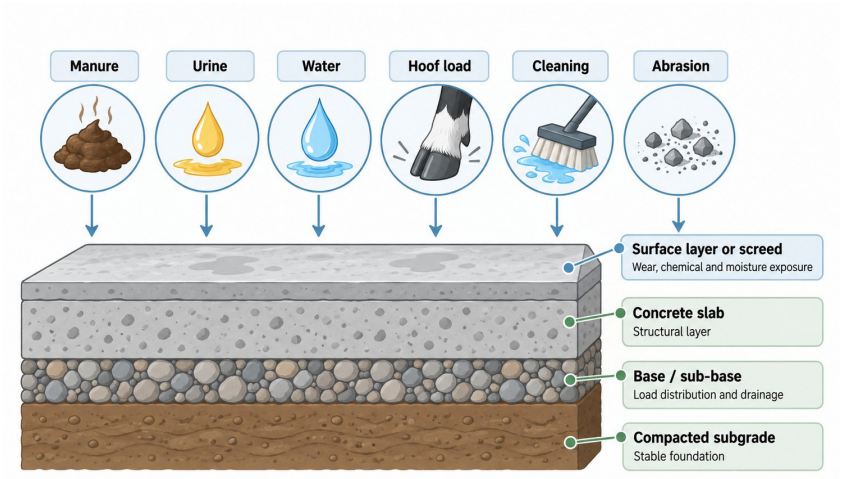


Fig. 3. Typical layered structure of a conventional concrete floor in cattle building and the main exposure zone [7, 16, 24, 25].

Table 3. Minimum practical technological requirements for concrete floorings in cattle buildings.

Technological parameter	Recommended requirement	Purpose in cattle buildings
Compressive strength class	At least C30/37 for zones exposed to manure and intensive traffic	Higher structural reserve and improved resistance to surface deterioration are provided.
Water - cement ratio	w/c ≤ 0.45	Capillary porosity and liquid penetration are limited.
Compaction and curing	Full compaction and sufficient curing must be ensured	Air voids, permeability and early surface weakness are reduced.
Surface drainage	A technological slope toward channels or manure alleys should be provided	Retention time of urine, washing water and manure liquid is reduced.
Surface texture	A non - slippery but cleanable surface is required	Animal safety is supported without excessive retention of organic matter.
Chemical protection	Protective coatings or resistant binders are required in highly aggressive zones	Acid, sulfate and microbial action on the cement matrix are limited.

**Compiled according to livestock flooring and concrete durability literature [7, 16, 24, 25].*

Table 4. Main components of cattle manure and their technological significance for concrete.

Component	Approximate content	Possible effect on concrete
Water	80 - 90 %	Moistening is maintained and the transport of aggressive ions is facilitated.
Organic matter	5 - 10 %	Microbiological activity and formation of organic acids are supported.
Nitrogen and ammoniacal compounds	0.3 - 0.6 % N; 0.05 - 0.2 % NH_3 - N	The pH and chemical activity of the environment are affected.
Sulfates	0.05 - 0.3 %	They are related to the risk of gypsum and ettringite formation.
Organic acids	About 0.5 %	Dissolution of calcium products and loss of surface density are caused.

removed by wear, diffusion is supported by moisture and dissolution, and structural weakening of the cement matrix are accelerated by the chemical products of manure [44 - 75].

TECHNOLOGICAL EVIDENCE FOR CHANGES IN CONCRETE PROPERTIES

Under acid exposure, mass loss, reduced compressive strength and alteration of the surface zone are reported; the generalized trends are summarized in Fig. 5 [49].

Sulfate attack leads to gypsum and ettringite formation, microcrack development and weakening of C - S - H phases. The principal stages of this process are summarized schematically in Fig. 6. The sequence emphasizes that concrete alteration is associated with phase transformations, internal stress, microcracking and changes in pore connectivity [57 - 61].

Mechanical abrasion should not be considered a secondary factor. The technological consequences of mechanical wear on flooring surfaces are summarized in Fig. 7. Such wear changes surface roughness and micro texture, increases the retention of organic matter and moisture, and prolongs the contact between concrete and the aggressive environment [1, 65 - 68].

The most direct link with cattle manure is provided by studies on cementitious and concrete materials

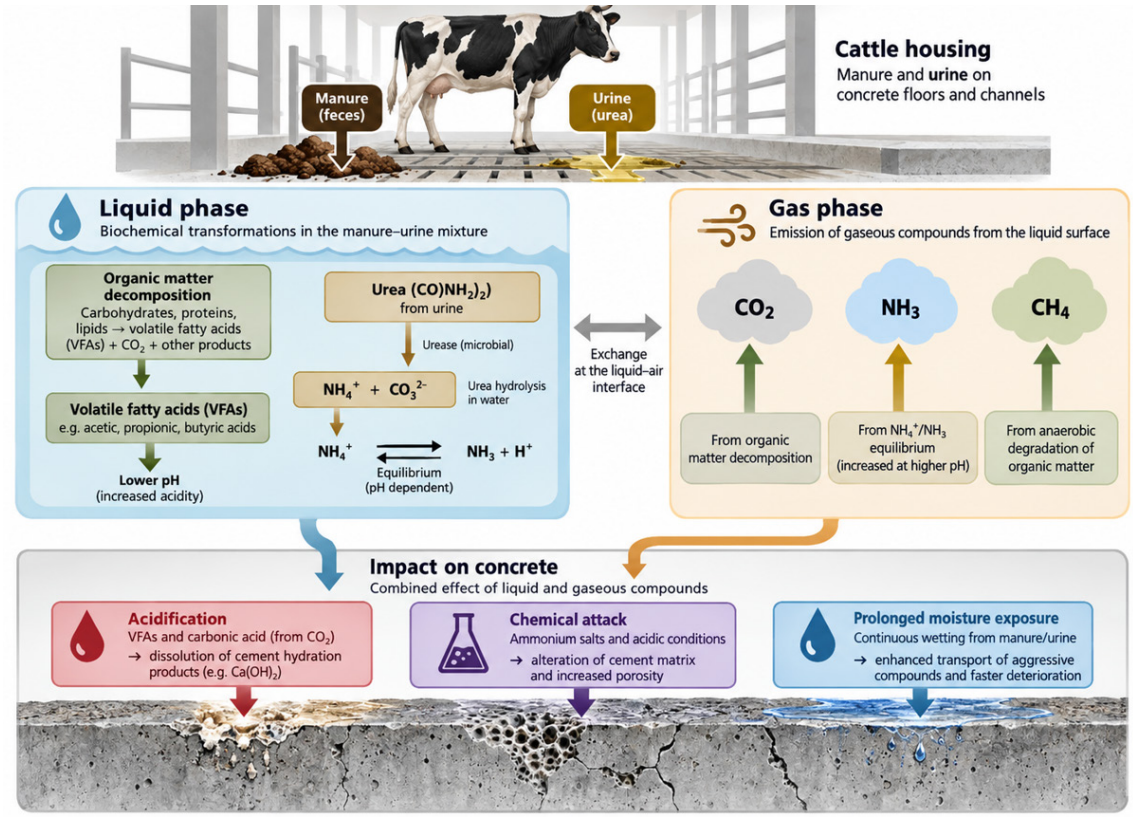


Fig. 4. Main biochemical processes during manure decomposition and the release of aggressive compounds [42, 43].

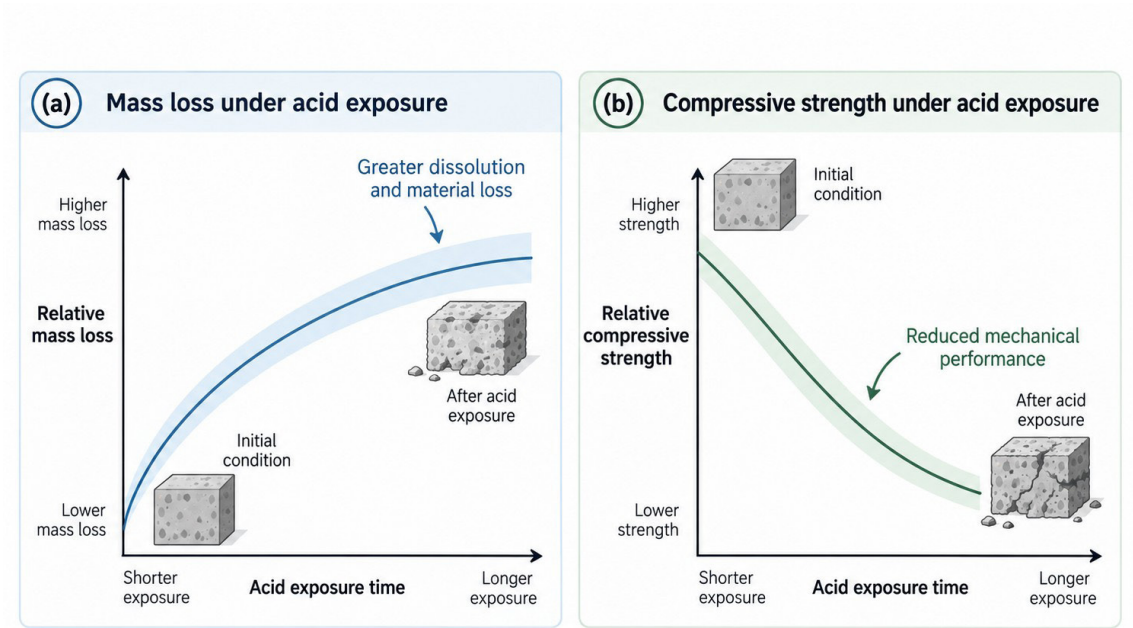


Fig. 5. Generalized trend of mass loss and compressive strength reduction of cement-based materials under acid exposure [49].

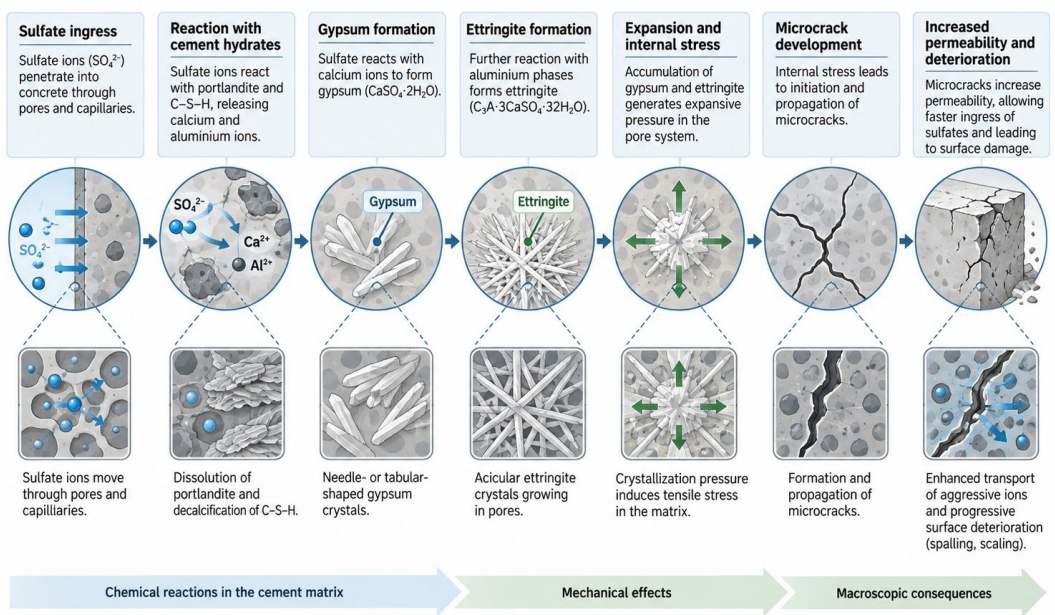


Fig. 6. Schematic mechanism of sulfate attack in the cement matrix [57 - 61].

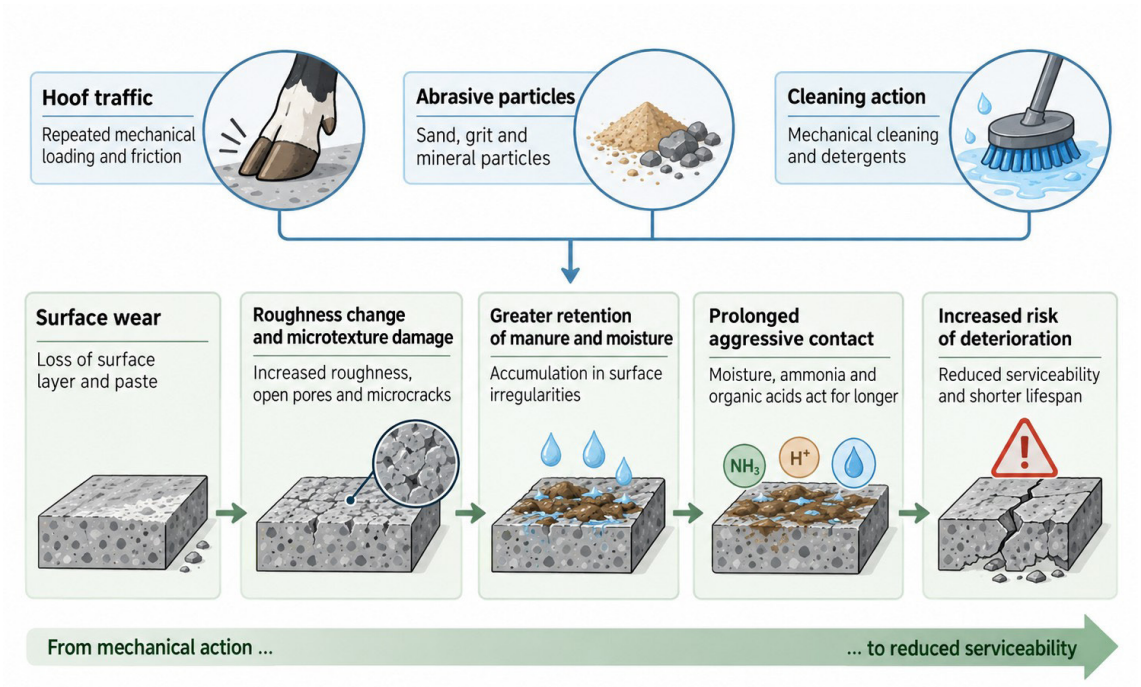


Fig. 7. Technological consequences of mechanical wear on flooring surfaces in cattle buildings [1, 65 - 68].

containing cattle manure or cattle manure ash. Although the real action of manure on hardened concrete is not fully reproduced by these studies, their results are technologically important because changes in thermal conductivity, water absorption, density, homogeneity and residual strength may be caused by organic and ash components [83 - 85].

Innovations and limitations of the current evidence

Studies on increasing concrete durability in an aggressive environment show that the resistance of the cement matrix can be improved using mineral admixtures, alternative binder systems and nanoscale modifiers.

The importance of slag, fly ash, silica fume and other alternative binders for microstructure densification, reduction of capillary porosity and limitation of aggressive ion penetration has been emphasized. These materials are especially important for concrete floorings exposed to moisture, organic acids, sulfate compounds and mechanical wear [18, 76, 77].

Geopolymer and self - healing concretes are also considered promising technological solutions. Better resistance in aggressive environments may be provided by these systems because of their lower content of free calcium hydroxide, denser structure and potential for limiting microcracks. However, their application in cattle buildings still requires additional experimental evidence, especially under prolonged contact with manure, urine and washing water [77, 79].

The use of cow dung ash and chickpea stalk ash as eco - friendly alternatives in cement mortars was investigated by Jamwal et al. [80]. Although these studies were not conducted directly under manure contact, the potential for the use of agricultural waste products as mineral additives was shown. This approach is important for the development of more sustainable and economically justified concretes applicable in agricultural infrastructure.

As an alternative to traditional Portland cement concrete, the application of geopolymer materials in an aggressive livestock environment was considered by Shcherban' et al. [49]. Geopolymers are characterized by an aluminosilicate structure in which the amount of free calcium hydroxide is significantly lower than in ordinary cement systems. As a result, the vulnerability

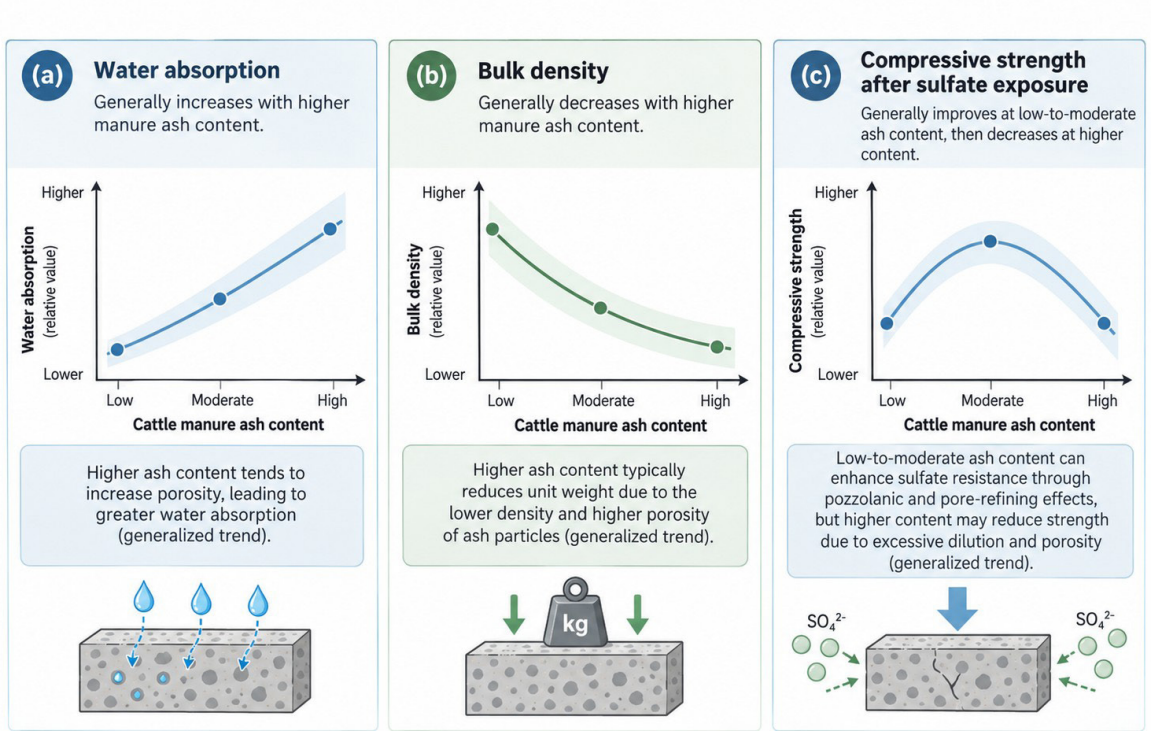


Fig. 8. Generalized influence of cattle manure ash content on selected physicomechanical properties of cement mortar [80].

of the material to acid attack, decalcification and surface deterioration is reduced.

A particularly promising direction is the use of graphene oxide (GO) as a nano additive in cementitious composites. Graphene oxide can limit microcrack development, improve the bond between hydration products and increase the density of the cement matrix. The mechanism of action is presented in Fig. 9. The addition of graphene oxide supports the formation of a more compact microstructure that hinders the penetration of water, acids and aggressive ions [81].

While graphene oxide supports the limitation of microcracks in the cement matrix, p - GO nanosheets are considered an additional protective component against acid and sulfate exposure. Penetration of aggressive ions can be reduced, and the resistance of the surface layer can be increased. As schematically summarized in Fig. 10, the modified microstructure may limit ion penetration, porosity, microcrack development and acid-related deterioration of the cement matrix [82].

A large part of the data was obtained under laboratory conditions or in analogous environments - sewer systems, biogas facilities, silage effluents and acid and sulfate solutions. These data prove the mechanisms but the real manure environment in cattle buildings cannot be fully reproduced by them. Therefore, future studies should combine laboratory exposure and field monitoring while compressive strength, water absorption, density, porosity, abrasive wear, microstructural changes and the risk of reinforcement corrosion are measured simultaneously.

The selection of a concrete system for floorings in cattle buildings should be based not only on the compressive strength class but also on resistance to moisture, organic acids, sulfate compounds, urine and mechanical wear. Suitable, limitedly suitable and unsuitable concrete systems for contact with manure are summarized in Table 5. A technological assessment is made according to the density of the structure, the water - cement ratio, chemical resistance and the need for additional protection.

From the presented assessment it is shown that ordinary concrete with a high water - cement ratio and C20/25 concrete without additional protection are not sufficiently reliable for prolonged contact with manure. Concretes with a higher strength class, low

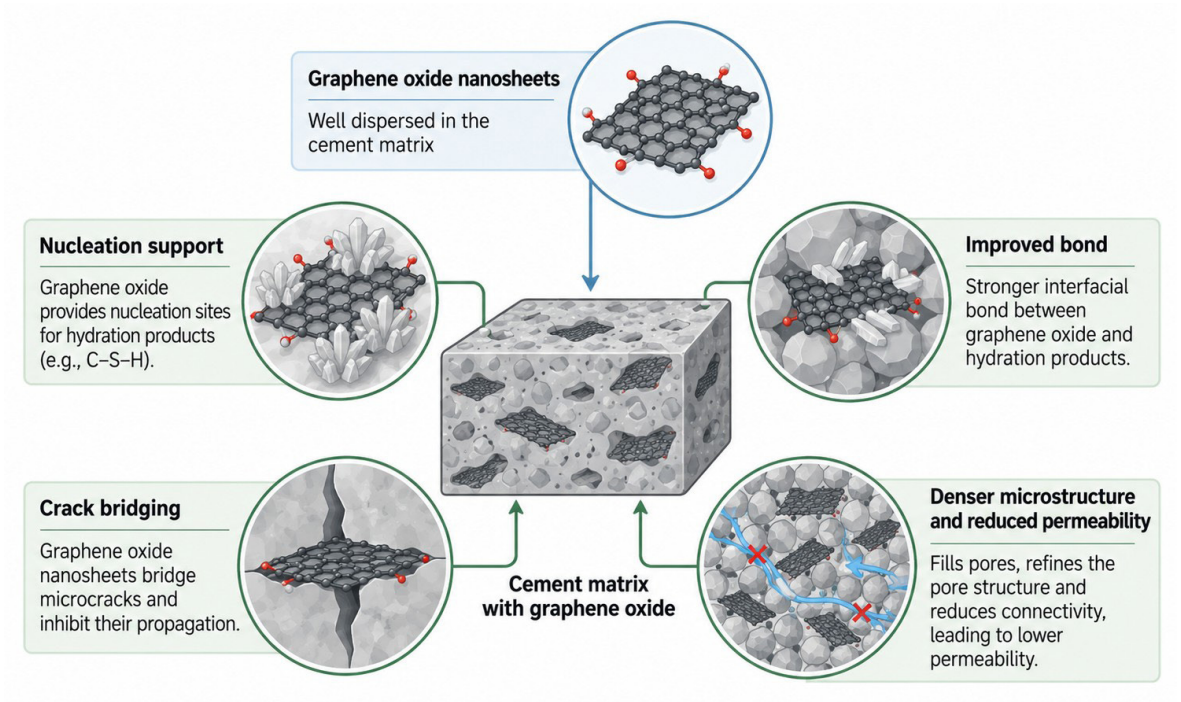


Fig. 9. Schematic representation of the mechanism of action of graphene oxide in the cement matrix [81].

w/c, sulfate - resistant cement and mineral admixtures are more suitable because porosity and the penetration of aggressive substances are limited. Geopolymer and alkali - activated concretes have innovative potential but their application under real livestock conditions requires additional long - term studies.

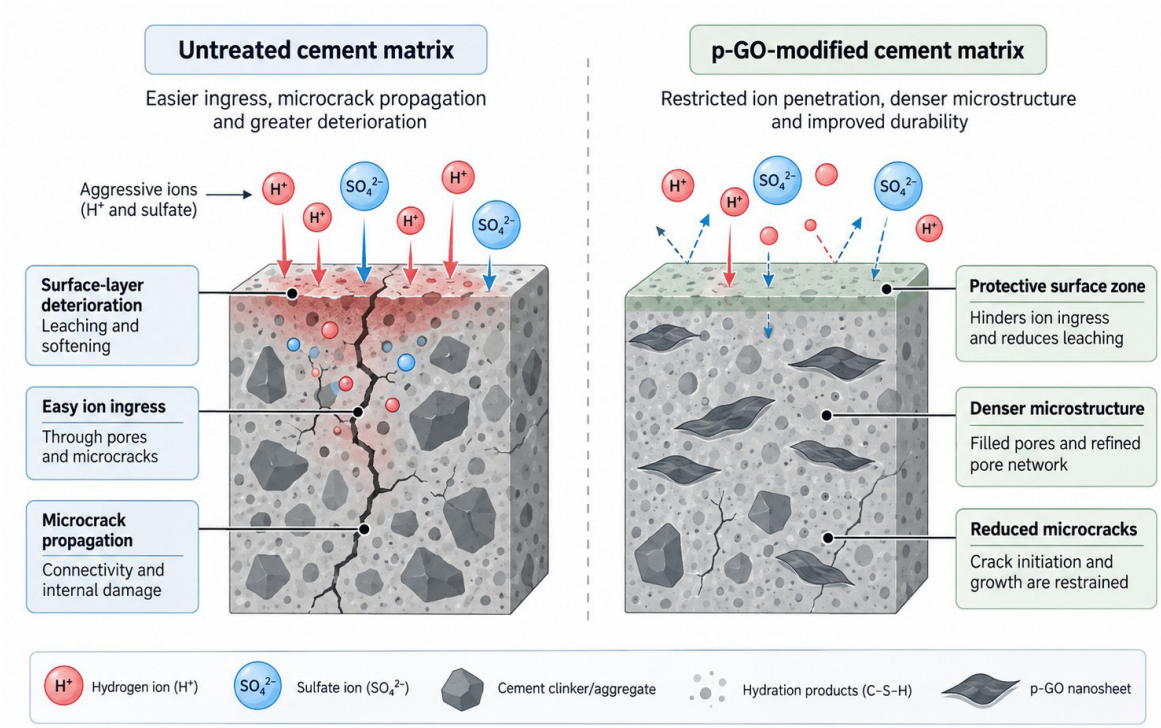


Fig. 10. Schematic representation of the protective effect of p - GO nanosheets on the cement matrix under aggressive exposure [82].

Table 5. Suitable and unsuitable concrete systems for contact with manure.

Concrete system	Assessment	Reason
Ordinary concrete with high w/c	Unsuitable	Increased porosity, easier penetration of aggressive liquids and lower chemical resistance.
C20/25 without additional protection	Limitedly suitable	It may be used for experimental comparison, but it is not sufficient for prolonged contact with manure.
C30/37 or higher with w/c ≤ 0.45	Suitable	A denser structure, better strength and lower permeability are provided.
Sulfate - resistant concrete	Suitable	The risk of sulfate attack and formation of destructive products is reduced.
Slag, pozzolanic and composite systems	Promising	The matrix can be densified and the transport of aggressive ions can be limited.
Geopolymer and alkali - activated concretes	Innovative but requiring verification	High chemical resistance is shown, but long - term field data for cattle buildings are required.

CONCLUSIONS

- Concrete deterioration in cattle buildings is a complex process in which acid attack, sulfate corrosion, microbiological action, calcium leaching and mechanical abrasion act simultaneously.
- Concrete intended for contact with manure should not be assessed only by compressive strength. Indicators of water absorption, density, porosity, permeability, sulfate resistance, acid resistance and wear resistance are required.
- From a technological point of view, concrete mixtures with a class of at least C30/37, w/c ≤ 0.45, a dense structure, good compaction, sufficient curing and a suitable drainage slope are more appropriate.
- Sulfate - resistant, slag, pozzolanic and composite cements are more suitable than ordinary Portland cement under prolonged contact with a moist and chemically aggressive livestock environment.
- Innovative systems - geopolymer, alkali - activated, self - healing and nano additive - modified systems - are promising, but they must be verified under real conditions with manure, urine, moisture and abrasion.
- An integrated experimental program is required so that laboratory indicators can be linked to the real behaviour of concrete floorings in cattle buildings.

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Authors' contributions

V.G. is responsible for the concept, literature selection, technological analysis, data interpretation, preparation of tables and figures, writing and final editing of the manuscript.

REFERENCES

1. R. Kuisma, H.-R. Kymäläinen, M. Hellstedt, P. Jauhiainen, J. Määttä, A.-M. Sjöberg, Properties and cleanability of new and traditional surface materials in cattle barns - a field study, Agric. Food Sci., 17, 2008, 227-239.
2. B. Svennerstedt, Durability of Building Materials and Components in Agricultural Environment, Swedish University of Agricultural Sciences, Alnarp, Sweden.
3. A. Chikhi, R. Billet, H. Benaddi, M. Tidjani, T. Lakhemissi, A. Berkia, M. Hadji, Impact of aggressive environments on the mechanical and physico-chemical properties of concrete, Stud. Eng. Exact Sci., 5, 2, 2024, 1-22. https://doi.org/10.54021/seesv5n2 - 402.
4. H. Hilbig, T. Gutberlet, R.E. Beddoe, Acid attack on hydrated cement: effect of organic acids on the degradation process, Mater. Struct., 57, 2024, 83. https://doi.org/10.1617/s11527-024-02360-8.
5. D. Wang, F. Guan, C. Feng, K. Mathivanan, R. Zhang, W. Sand, Review on Microbially Influenced Concrete Corrosion, Microorganisms, 11, 8, 2023, 2076. https://doi.org/10.3390/microorganisms11082076.
6. D. Dinev, N. Delchev, V. Dimova, Agricultural Buildings, Stara Zagora, Academic Publishing House, Trakia University, 2017. ISBN 978-954-338-140-1.
7. D. Georgiev, Test Rig for Investigation of Adhesion and Friction of Cow Hooves on Different Floorings in Industrial Dairy Farms, Stara Zagora, Academic Publishing House, Trakia University, 2022. ISBN 978-954-338-183-8.
8. C. Nilsson, Use of concrete for floors in livestock buildings, Proceedings of the Vth International Symposium Concrete for a Sustainable Agriculture - Agro-, Aqua and Community Application, San Lorenzo de El Escorial, Spain, 2005, 25-32.
9. C. Phillips, Principles of Cattle Production, 2nd ed., Wallingford, CABI Publishing, 2010. ISBN 978-1-84593-397-5.
10. RÖFIX, Concrete Handbook, RÖFIX, 2013. https://cdn.dam.fixit-holding.com/assets/api/fd2c2da5098b4611a02f155d5d8c0847/original/%D0%9D%D0%B0%D1%80%D1%8A%D1%87%D0%BD%D0%B8%D0%BA-%D0%B7%D0%B0-%D0%B1%D0%B5%D1%82%D0%BE%D0%BD.pdf, accessed 11 January 2026.
11. P.P.F. Brasileiro, Y.B. Brandão, L.A. Sarubbo, M. Benachour, Self-Healing Concrete: Background,

Development, and Market Prospects, Biointerface Res. Appl. Chem., 11, 6, 2021, 14709-14725. https://doi.org/10.33263/BRIAC116.1470914725.
12. V. Kardzhiev, Lecture Notes on Reinforced Concrete and Reinforced Concrete Structures, Sofia, University of Architecture, Civil Engineering and Geodesy, 2011-2013. https://www.scribd.com/document/446873493, accessed 8 February 2026.
13. Ts. Krastev, Structural Mechanics, Sofia, Tehnika, 1990. https://eclipse.uacg.bg/catalog/view/LG7JYTN6MW, accessed 5 May 2026.
14. Y. Simeonov, Construction Materials, Sofia, Tehnika, 1991. https://eclipse.uacg.bg/catalog/view/QRP81ELZ8G, accessed 5 May 2026.
15. EN 1992 - 1 - 1:2004, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, European Committee for Standardization, Brussels, 2004.
16. A. Neville, Properties of Concrete, 5th ed., London, Pearson Education, 2011. ISBN 9780-273-75580-7.
17. M. Nehdi, A. Soliman, Early-age properties of concrete: Overview of fundamental concepts and state-of-the-art research, Proc. Inst. Civ. Eng. Constr. Mater., 164, 2, 2011, 57-77. https://doi.org/10.1680/coma.900040.
18. M. Thomas, Supplementary Cementing Materials in Concrete, Boca Raton, CRC Press, 2013. https://doi.org/10.1201/b14493.
19. P. Woyciechowski, P. Wolinski, G. Adamczewski, Prediction of carbonation progress in concrete containing calcareous fly ash co-binder, Materials, 12, 17, 2019, 2665. https://doi.org/10.3390/ma12172665.
20. BDS EN 206:2013+A2:2021/NA:2021, Concrete. Specification, performance, production and conformity. National Annex, Bulgarian Institute for Standardization, 2021.
21. M. Krstic, J. Davalos, E. Rossi, S. Chaves Figueiredo, O. Copuroglu, Freeze-thaw resistance and air-void analysis of concrete with recycled glass-pozzolan using X-ray micro-tomography, Materials, 14, 1, 2021, 154. https://doi.org/10.3390/ma14010154.
22. T. Koroudjex, H. Eskandari-Hadaf, Evaluation of the mechanical properties and microstructure of cement mortar with different cement strength classes using image analysis, Arab. J. Sci. Eng., 47, 2022, 4763-4783. https://doi.org/10.1007/s13369-021-06257-4.
23. BDS EN 197-1:2011/NA:2023, Cement. Part 1: Composition, specifications and conformity criteria for common cements. National Annex, Bulgarian Institute for Standardization, 2023.
24. American Concrete Institute, Guide to Durability of Concrete, ACI Committee 201, American Concrete Institute, Farmington Hills, MI, USA, 2021.
25. Dairyland Initiative, Dairy Housing and Flooring Guidelines, University of Wisconsin-Madison, 2015. https://thedairylandinitiative.vetmed.wisc.edu/adult-cow-housing/flooring/, accessed 6 March 2026.
26. B. Amon, V. Kryvoruchko, T. Amon, S. Zechmeister-Boltenstern, Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry, Agric. Ecosyst. Environ., 112, 2006, 153-162. https://doi.org/10.1016/j.agee.2005.08.030
27. M. Kiliswa, M. Alexander, Biogenic corrosion of concrete sewer pipes: A review of the performance of cementitious materials, Proceedings of the XIII DBMC International Conference, São Paulo, Brazil, 2014.
28. S. Larreur-Cayol, L. De Windt, A. Bertron, G. Escadeillas, Deterioration of cementitious materials by organic acids in agricultural effluents: Experiments and modelling, Waste Manage., 31, 6, 2011, 1183-1192. https://doi.org/10.1016/j.wasman.2011.01.021.
29. C. Burton, C. Turner, Manure Management: Treatment Strategies for Sustainable Agriculture, 2nd ed., Silsoe, Silsoe Research Institute, 2003. ISBN 0-9531282-6-1.
30. S. Sommer, M. Christensen, T. Schmidt, L. Jensen, Animal Manure Recycling: Treatment and Management, Oxford, Wiley-Blackwell, 2013. ISBN 978-1-118-48853-9.
31. C. Rotz, Management to reduce nitrogen losses in animal production, J. Anim. Sci., 82, E-Suppl., 2004, E119-E137. https://doi.org/10.2527/2004.8213_supplE119x.
32. T. Vogeler, S. Thomas, T. Van der Weerden, Effect of irrigation management on pasture yield and nitrogen losses, Agric. Water Manage, 216, 2019, 60-69. https://doi.org/10.1016/j.agwat.2019.01.022.
33. G. Zhu, X. Ma, Z. Gao, W. Ma, J. Li, Z. Cai, Characterizing CH_4 and N_2O emissions from an intensive dairy operation in summer and fall in China, Atmos. Environ., 83, 2014, 245-253. https://

doi.org/10.1016/j.atmosenv.2013.11.001.
34. C. Rose, A. Parker, B. Jefferson, E. Cartmell, The characterization of feces and urine: A review of the literature to inform advanced treatment technology, Crit. Rev. Environ. Sci. Technol., 45, 17, 2015, 1827-1879. https://doi.org/10.1080/10643389.2014.1000761.
35. G. Sassenrath, J. Schneider, R. Gaj, W. Grzebisz, Nitrogen balance as an indicator of environmental impact: Toward sustainable agricultural production, Renew. Agric. Food Syst., 28, 3, 2013, 276-289. https://doi.org/10.1017/S1742170512000166.
36. S. Sommer, J. Olesen, S. Petersen, M. Weisbjerg, L. Valli, L. Rodhe, F. Béline, Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones, Glob. Change Biol., 15, 12, 2009, 2825-2837. https://doi.org/10.1111/j.1365-2486.2009.01888.x.
37. T. Yasmin, A. Jabeen, S. Iram, F. Arshad, M. Waheed, A. Hashem, G. Quezada, E. Abd Allah, Environmental impacts of livestock management strategies in subtropical agroecosystems, Cogent Food Agric., 11, 1, 2025, 2562171. https://doi.org/10.1080/23311932.2025.2562171.
38. T. Penev, K. Stankov, Effect of lameness on milk production traits in Holstein-Friesian dairy cows, Vet. Zootech., 70, 92, 2015, 5-58.
39. AgriTraction, Why barn floors are slippery, 2023. https://www.agritraction.com/why-barn-floors-are-slippery, accessed 26 March 2026.
40. M. Gaworski, M. Boćkowski, Comparison of cattle housing systems based on the criterion of damage to barn equipment and construction errors, Animals, 12, 19, 2022, 2530. https://doi.org/10.3390/ani12192530.
41. J. Leskovec, M. Voljč, S. Žgur, Effect of a high welfare floor and a concrete slatted floor on the growth performance, behavior and cleanliness of Charolais and Limousin heifers: A case study, Animals, 12, 7, 2022, 859. https://doi.org/10.3390/ani12070859
42. X. Flotats, Emissions (I): How are greenhouse gas and ammonia emissions produced on our farms?, 333, 2023. https://www.3tres3.com/en/articles/how-are-ghg-and-ammonia-emissions-produced-on-farms_19357, accessed 5 April 2026.
43. Z. Gao, L. Zhi, Y. Yang, W. Ma, W. Liao, J. Li, Y. Cao, M. Roelcke, Greenhouse gas emissions from the enteric fermentation and manure storage of dairy and beef cattle in China during 1961-2010, Environ. Res., 135, 2014, 111-119. https://doi.org/10.1016/j.envres.2014.08.030.
44. W. Sand, E. Bock, Biodeterioration of mineral materials by microorganisms - biogenic sulfuric and nitric acid corrosion of concrete and natural stone, Geomicrobiol. J., 9, 2-3, 1991, 129-138. https://doi.org/10.1080/01490459109385944.
45. J. Monteny, E. Vincke, A. Beeldens, N. De Belie, L. Taerwe, D. Van Gemert, W. Verstraete, Chemical, microbiological and in situ test methods for biogenic sulfuric acid corrosion of concrete, Cem. Concr. Res., 30, 4, 2000, 623-634. https://doi.org/10.1016/S0008-8846(00)00219-2
46. L. Wu, G. Huang, W.V. Liu, Methods to evaluate resistance of cement-based materials against microbially induced corrosion: A state-of-the-art review, Cem. Concr. Compos., 123, 2021, 104208. https://doi.org/10.1016/j.cemconcomp.2021.104208.
47. C. Voegel, A. Bertron, B. Erable, Biodeterioration of cementitious materials in biogas digester, Mater. Tech., 103, 2, 2015. https://doi.org/10.1051/mattech/2015023.
48. J.P. Godinho, M.H.F. Medeiros, A.A. Melo Neto, V.M.E. Lima, D.J. De Souza, Laboratory-field assessment of concrete exposed to biogenic sulphuric acid: Influence of SCM-based binders on long-term degradation, Constr. Build. Mater., 493, 2025, 143185. https://doi.org/10.1016/j.conbuildmat.2025.143185.
49. E.M. Shcherban', S.A. Stel'makh, A. Beskopylny, L.R. Mailyan, B. Meskhi, Increasing the Corrosion Resistance and Durability of Geopolymer Concrete Structures of Agricultural Buildings Operating in Specific Conditions of Aggressive Environments of Livestock Buildings, Appl. Sci., 12, 3, 2022, 1655. https://doi.org/10.3390/app12031655.
50. L. De Windt, A. Bertron, S. Larreur-Cayol, G. Escadeillas, Interactions between hydrated cement paste and organic acids: Thermodynamic data and speciation modeling, Cem. Concr. Res., 69, 2015, 25-36. https://doi.org/10.1016/j.cemconres.2014.12.001.
51. R. Chromková, R. Čechmánek, Effect of agents of organic origin on concrete degradation, IOP Conf. Ser.: Mater. Sci. Eng., 379, 1, 2018, 012040. https://

doi.org/10.1088/1757-899X/379/1/012040.
52. S. Pavía, Study of the durability of OPC versus GGBS concrete on exposure to silage effluent, J. Mater. Civ. Eng., 20, 4, 2008, 313-320. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:4(313).
53. R. Chromková, R. Čechmánek, M. Krejčí Kotlánová, Effect of silages on concrete and process of its corrosion in the course of time, J. Phys.: Conf. Ser., 2792, 1, 2024, 012013. https://doi.org/10.1088/1742-6596/2792/1/012013.
54. M. Gebrehanna, R. Gordon, A. Madani, A. VanderZaag, J. Wood, Silage effluent management: A review, J. Environ. Manage., 143, 2014, 113-122. https://doi.org/10.1016/j.jenvman.2014.04.012.
55. C.M. Ninan, R. Radhakrishnan, K.P. Ramaswamy, R. Sajeeb, Investigation on Aggressiveness of Organic Acids on Degradation of Ordinary Portland Cement Mortar, AIJR Proceedings, Proceedings of the 6th International Conference on Modeling and Simulation in Civil Engineering, 2023, 34-39. https://doi.org/10.21467/proceedings.156.
56. C.M. Ninan, K.P. Ramaswamy, R. Sajeeb, A novel approach towards ranking the performance of cement-based materials exposed to organic acids, Innovative Infrastructure Solutions, 9, 2024, 279. https://doi.org/10.1007/s41062-024-01595-2.
57. J. Skalny, J. Marchand, I. Odler, Sulfate Attack on Concrete, London and New York, Spon Press, 2002. ISBN 0-203-34224-0.
58. J. Trägårdh, F. Bellmann, Sulphate attack, in: Durability of Self-Compacting Concrete, RILEM Publications, 2007, 89-118. ISBN 978-2-35158-048-6.
59. E. Hewayde, M. Nehdi, E. Allouche, G. Nakhla, Effect of mixture design parameters and wetting-drying cycles on resistance of concrete to sulfuric acid attack, J. Mater. Civ. Eng., 19, 2, 2007, 155-163. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:2(155).
60. P.W. Ariyadasa, A.C. Manalo, W. Lokuge, V. Aravinthan, A. Gerdes, J. Kaltenbach, B. Arevalo Galvan, Macro and microstructural evolution of low-calcium fly ash-based geopolymer mortar exposed to sulphuric acid corrosion, Cem. Concr. Res., 178, 2024, 107436. https://doi.org/10.1016/j.cemconres.2024.107436.
61. M.M. Sherief, R.A. Shittu, F.I. Alhamadi, A. Alkaabi, A. Alfantazi, Concrete Durability in Arid Region: Influence of Seasonal Temperature and Humidity Variation on Sulfate Attack on Modified Cement Mortar, Int. J. Concr. Struct. Mater., 20, 2026, 44. https://doi.org/10.1186/s40069-026-00917-1.
62. P.S. Sajeev, V.S.G. Rajagopal, N.A. Arasu, Investigation of concrete durability enhancement using supplementary cementitious materials, MethodsX, 15, 2025, 103527. https://doi.org/10.1016/j.mex.2025.103527.
63. E. Janowska-Renkas, D. Fabianowski, I. Klementowski, K. Borek, A. Koniuszy, G. Wałowski, Gas Permeability of the Anisotropic Structure of a Frame Made of Concrete with the Addition of a Biocomponent-Application in Livestock Buildings, Materials, 19, 11, 2026, 2257. https://doi.org/10.3390/ma19112257.
64. G. Sun, Y. Li, L. Zhang, C. Li, H. Yang, Numerical simulation of calcium leaching and damage in concrete pipes under flowing water, Case Stud. Constr. Mater., 2025, e05098. https://doi.org/10.1016/j.cscm.2025.e05098.
65. J. Määttä, M. Hellstedt, R. Kuisma, H.-R. Kymäläinen, R. Mahlberg, A.-M. Sjöberg, Effects of chemical and mechanical wearing on the cleanability and surface properties of traditional and new surface materials in cattle barns - a laboratory study, Biosyst. Eng., 103, 2009, 464-473.
66. N. Banthia, R. Gupta, Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete, Cem. Concr. Res., 36, 7, 2006, 1263-1267.
67. E. Telezhenko, M. Magnusson, C. Bergsten, Gait of dairy cows on floors with different slipperiness, J. Dairy Sci., 100, 8, 2017, 6494-6503. https://doi.org/10.3168/jds.2016-12208.
68. A. Sharma, U. Kennedy, C.J.C. Phillips, A novel method of assessing floor friction in cowsheds and its association with cow health, Animals, 9, 4, 2019, 120. https://doi.org/10.3390/ani9040120.
69. V. Assaad, J.C. Jofriet, S. Negi, G. Hayward, Sulfide and sulfate corrosion of concrete in livestock buildings, ASAE Annual International Meeting, Chicago, IL, USA, 28-31, July 2002. https://doi.org/10.13031/2013.10471.
70. J.C. Jofriet, M. Abdelmseeh, S. Negi, G. Hayward, Deterioration of reinforced concrete in farm buildings due to sulfate and sulfide attack, ASAE/CSAE Annual International Meeting, 2004. https://

doi.org/10.13031/2013.16796.
71. C. Maraveas, Durability issues and corrosion of structural materials and systems in farm environment, Appl. Sci., 10, 3, 2020, 990. https://doi.org/10.3390/app10030990.
72. O. Shkromada, T. Fotina, R. Petrov, L. Nagorna, O. Bordun, M. Barun, O. Babenko, M. Karpulenko, T. Tsarenko, V. Solomon, Development of a method of protection of concrete floors of animal buildings from corrosion at the expense of using dry disinfectants, Eastern-European J. Enterp. Technol., 4, 6, 112, 2021, 33-40. https://doi.org/10.15587/1729-4061.2021.236977.
73. O. Shkromada, T. Fotina, Y. Dudnyk, R. Petrov, V. Levytska, V. Chivanov, N. Bogatko, A. Pikhtirova, O. Bordun, Reducing the biogenic corrosion of concrete in a pigsty by using disinfectants, Eastern-European J. Enterp. Technol., 4, 6, 118, 2022, 57-66. https://doi.org/10.15587/1729-4061.2022.263310.
74. T. Fotina, V. Petrov, H. Havryliuk, Y. Liashenko, L. Varenyk, Improving the technique of protecting concrete floors in poultry houses, Eastern-European J. Enterp. Technol., 3, 6, 123, 2023, 66-76. https://doi.org/10.15587/1729-4061.2023.282127.
75. M. Giroudon, M. Fourré, I. Frigout, A. Bertron, Degradation of concrete panels in air scrubbers, Case Stud. Constr. Mater., 23, 2025, e05035. https://doi.org/10.1016/j.cscm.2025.e05035.
76. Z. Gong, D. Thompson, T. Aiken, D. McPolin, S. Nanukuttan, Resistance of ternary cement-based and alkali-activated concretes against silage effluent attack, Constr. Build. Mater., 457, 2024, 139439. https://doi.org/10.1016/j.conbuildmat.2024.139439.
77. P. Chindaprasirt, P. Kanchanda, A. Sathonsaowaphak, H. Cao, Sulfate resistance of blended cements containing fly ash and rice husk ash, Constr. Build. Mater., 21, 6, 2007, 1356-1361. https://doi.org/10.1016/j.conbuildmat.2005.10.005.
78. I.M. Elgendy, N.E. Elkaliny, H.M. Saleh, G.O. Darwish, M.M. Almostafa, K. Metwally, G. Yahya, Y.A.-G. Mahmoud, Bacteria-powered self-healing concrete: Breakthroughs, challenges, and future prospects, J. Ind. Microbiol. Biotechnol., 52, 2025, kuae051. https://doi.org/10.1093/jimb/kuae051.
79. M. Łach, A. Przybek, K. Setlak, P. Bazan, M. Hebdowska-Krupa, Resistance of low-emission geopolymer binders with fibers to aggressive external factors, Struct. Environ., 16, 3, 2024, 134-140. https://doi.org/10.30540/sae-2024-012.
80. A. Jamwal, A. Nautiyal, K. Singh, S. Alam, N.A. Alselami, K.M. Aati, Sustainable Concrete Production: Utilizing Cow Dung Ash and Corn Stalk Ash as Eco-Friendly Alternatives, Civil Engineering Journal, 10, Special Issue, 2024, 21-36. https://doi.org/10.28991/CEJ-SP2024-010-02.
81. Z. Chen, S. Wang, H. Sui, X. Xu, W. Qian, X. Ge, Y. Liu, Y. Gao, Mechanisms of graphene oxide enhancement of freeze-thaw durability in cementitious composites, J. Build. Eng., 114, 2025, 114348. https://doi.org/10.1016/j.jobe.2025.114348.
82. A. Anwar, X. Liu, T. Ngo, M. Sharma, L. Zhang, Degradation resistance of graphene oxide-tailored ternary blended concrete under prolonged sulfuric acid exposure, Cem. Concr. Res., 2026, 108215. https://doi.org/10.1016/j.cemconres.2026.108215.
83. Y. González, C. Miranda-Cantillo, J. Quintero-Torres, J.D. Rhenals-Julio, A.F. Jaramillo, J.J. Cabello-Eras, Substitution of sand in concrete blocks with coconut fiber and cattle manure: Effects on compressive strength and thermal conductivity, Buildings, 14, 10, 2024, 3092. https://doi.org/10.3390/buildings14103092.
84. A. Korkmaz, S. Şahin, Determination of some properties of lightweight concrete produced by partial replacement of cattle manure ash instead of cement, Turkish Journal of Agriculture-Food Science and Technology, 12, 11, 2024, 1900-1907. https://doi.org/10.24925/turjaf.v12i11.1900-1907.6944.
85. M.A. Worku, W.Z. Taffese, B.Z. Hailemariam, M.D. Yehualaw, Cow dung ash in mortar: An experimental study, Applied Sciences, 13, 10, 2023, 6218. https://doi.org/10.3390/app13106218.