Cement and Concrete Composites 123 (2021) 104193

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Trenchless rehabilitation for concrete pipelines of water infrastructure: A review from the structural perspective

He Zhu [a], Tianyu Wang [a,b], Yichao Wang [a,c], Victor C. Li [a,*]

[a] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, 48109, USA
[b] College of Engineering, China University of Geosciences-Wuhan, Wuhan, Hubei Province, 430074, China
[c] Department of Disaster Mitigation for Structures, College of Civil Engineering, Tongji University, Shanghai, 200092, China

ARTICLE INFO

Keywords:
Concrete pipe
Trenchless
Rehabilitation
Retrofit
Engineered cementitious composites (ECC)
Spray

ABSTRACT

Concrete-based pipelines or linings are widely used for water and sewer systems. However, concrete pipes suffer from the problems of aging and deterioration due to complex loading (internal and external), severe service environments, and the brittle nature of concrete. This paper provides a state-of-the-art review of trenchless rehabilitation methods for concrete pipelines, including spray-in-place, grouting, sliplining, modified sliplining, cure-in-place pipe, close-fit, and fiber-reinforced polymer lining. In addition, an emerging structural retrofit method with Engineered Cementitious Composites (ECC) was introduced. The rehabilitation methods were classified into non-structural, semi-structural, structural, as well as the retrofit of structure and function. The technical features, advantages, drawbacks, and application conditions of each method were summarized to provide the basis for method selection. ECC can be applied as a coating by manual spraying and centrifugal spraying methods. The tailored characteristic of self-stressing enhances the integrity of the ECC liner and host pipe. The intrinsic advantages of ultra-high tensile ductility, anti-corrosion, jointless technique, tiny crack widths, self-healing behavior, as well as low cost make ECC a sustainable and resilient material for pipe rehabilitation and retrofit with increased load capacity, enhanced durability, and leakage-proof performance.

1. Introduction

Water pipelines work as arteries/veins for modern cities conveying both potable and wastewater, which are crucial for human society [1]. Some water pipelines have been in service for decades in developed countries, while new pipelines are being constructed in developing countries to support continuing urbanization. For instance, more than 0.5 million km of drainage pipelines have been installed in China since 2015, with future expansion at a rate of 10 % annually [2]. There are approximately 1.6 million km of drinking water pipelines [3] and 2.0 million km of wastewater pipelines in the U.S. [4], most of which were constructed in the 1950s and 1960s. According to ASCE [3], the grade of the water system dropped from B to D between 1988 and 2009 and has remained so up to the present, suggesting an urgent need for rehabilitation. The American Water Works Association indicated that at least US $1 trillion is needed for renewing the existing water/sewer pipe systems [3].

Concrete has advantages of good mechanical performance, low cost, wide availability, and can be easily produced with different diameters and lengths, which are attractive for pipeline manufacturing [5,6]. For sewer pipelines, traditional materials include (reinforced/prestressed/polymer) concrete pipe, brick pipe, and vitrified clay pipe. Concrete pipelines make up more than 50 % of the sewer system in the US [7], especially for those with a large diameter (>1 m) [5,6]. With regard to potable water pipes, cast iron, ductile iron, asbestos cement, PVC, and prestressed/reinforced concrete pipes are more popular, since water pressure leads to tensile hoop stress that may cause plain concrete to crack. However, cast/ductile iron pipes are usually lined with cement or concrete [8] to enhance corrosion resistance. Cement-based liner/pipes, as well as the asbestos cement pipe, also constitute approximately 50 % of the drinking water pipeline system [7,9]. Therefore, concrete and cement-based composites are the most widely used materials for water pipelines.

Aging concrete pipelines are prone to structural and hydraulic failures [10]. The complex working conditions, such as poor bedding, excess external loading, internal pressure, and temperature fluctuation, could cause cracking due to the brittle nature of concrete [7,9–11]. Cracks may be circumferential, longitudinal, spiral, or along joint

---

* Corresponding author.
E-mail addresses: zhuhe@umich.edu (H. Zhu), tiawang@umich.edu (T. Wang), yicwang@umich.edu (Y. Wang), vcli@umich.edu (V.C. Li).

https://doi.org/10.1016/j.cemconcomp.2021.104193
Received 2 October 2020; Received in revised form 18 April 2021; Accepted 19 July 2021

directions, which could result in leakage and structural failure [12]. Apart from structural failure, grease build-up, sediment, and encrustation could lead to the blockage and decrease of hydraulic capacity of the pipe [7,9]. Additionally, the combination of high sulfate concentration, high temperature, and low pH of wastewater provides an environment inductive to the growth of sulfur-oxidizing bacteria (SOB), which produces sulfuric acid that makes concrete wastewater pipe vulnerable to acid corrosion [13]. The corroded concrete pipe could subsequently crack, spall, and lose strength. The resulting decreased thickness of concrete pipe/liner weakens the load capacity, and could eventually lead to structural failure. Concrete pipe failure, involving pipe bursting, urban flooding, traffic disruption, and contamination of water, has significant economic and environmental costs. When operating with a utility tunnel [14], the failure of a concrete pipeline may shut down the whole utility system. Hence, the rehabilitation of deteriorated pipelines before their failure is imperative.

The selection of which pipeline rehabilitation approach to use depends on the failure mechanism and host pipe condition, including the degree of corrosion, structural deterioration, and hydraulic capacity loss [15]. In this study, the pipe conditions are defined as follows (according to Ref. [16]):

Partially deteriorated: The existing pipe is sound enough to support live/dead load, and after the repair, the host pipe could work together with the new liner. The deterioration type may include internal/external corrosion, leakage, and local cracks.

Fully deteriorated: The existing pipe cannot support the soil and live loads (both internal and external pressure). The condition is evident, such as pipe missing, losing its original shape, and collapse. The fully deteriorated pipe usually needs to be replaced with a new pipe [17,18]. This case falls outside the scope of this review article.

Compared with conventional open-cut methods, trenchless rehabilitation of concrete pipes has the advantages of being cost-effective, less disturbance to the ground (traffic and residents), environmentally friendly, and fast construction. The trenchless rehabilitation methods of concrete pipelines include spray-in-place (SIPP), grouting, sliplining (SL), modified sliplining (MSL), cure-in-place pipe (CIPP), close-fit, and fiber-reinforced polymer (FRP) [19,20]. While the current trenchless rehabilitation methods can obtain a non-structural/semi-structural/structural effect, an emerging repair material called Engineered Cementitious Composites (ECC) [21] shows the prospect of structural as well as functional retrofit for pipelines under both internal pressure and external loadings. The trenchless rehabilitation of pipelines has been reviewed from the perspective of application field such as water [22], sewer [4,15,23,24], and oil/gas [19]; or by methods/materials, e.g., CIPP [25,26], geopolymer [27], and FRP [28,29]. However, to the best knowledge of the authors, no review has been conducted for concrete pipeline rehabilitation from the perspective of structural effect.

The objective of this work is to provide a state-of-the-art review of trenchless rehabilitation methods for concrete pipelines with a focus on the structural effect, encompassing the well-known methods of SIPP, SL, MSL, CIPP, grouting, FRP, and close-fit, but also including an innovative ECC retrofit technology. The technical features, advantages, drawbacks, and application conditions are summarized to provide the basis for method selection. Finally, sprayed ECC is proposed as a sustainable and resilient approach for functional and structural rehabilitation and retrofit.

2. Non-structural rehabilitation

Non-structural rehabilitation is primarily utilized to protect the pipe from corrosion or to stop leakage. The new liner is not intended to provide structural support, and cannot withstand the internal pressure and external loadings [8,30]. This method includes the classes of spray-in-place pipe and grouting methods (Fig. 1).

2.1. Spray-in-place pipe (SIPP)

Internal coating with cement-based materials, geopolymer, and polymeric materials have been applied to protect and renew water/sewer infrastructures. The new liner could stop leakage and provide a corrosion protective layer for the host pipe. However, the internal surface of the concrete pipe requires extensive cleaning, and all active infiltration should be stopped before the application of the coating material [5]. The surface preparation is crucial for assuring the adhesion of the host pipe and coating material, which further influences the rehabilitation quality.

Coating materials can be either hand- or spray-applied onto the host pipe. For the small-diameter pipe without man-entry (<0.75 m (30 inches)), the coating materials are usually centrifugally sprayed by a spin-caster (Fig. 2 (a)). The rotary head fixed on a vehicle is driving by a pneumatic motor, and the materials are sprayed out by centrifugal force. For large-diameter pipes allowing worker-entry (>0.75 m (30 inches)), the coating liner can be applied robotically or by hand-held spray equipment (Fig. 2 (b)) as well as with the spin-cast method.

2.1.1. Cementitious material

Cement-based lining was first applied in the 1900s and remains one of the most used lining methods today [8,32]. Water pipes (cast/ductile iron pipe) lined with cementitious material before installation has become a standard method. Similarly, cement-based lining is widely adopted in sewer pipes [4]. Although conventional Portland cement is vulnerable to acid-corrosion in the sewer environment, calcium aluminate cement (CA) or calcium sulphoaluminate cement (CSA) can provide higher sulfide resistance [33]. Besides, the rapid hardening of CA and CSA decreases the bypass duration, mitigating the impacts caused by pipe shutdown [34].

Due to the brittle characteristic of cementitious materials, cracks are easily generated under tensile stress. Internal pressure or uneven

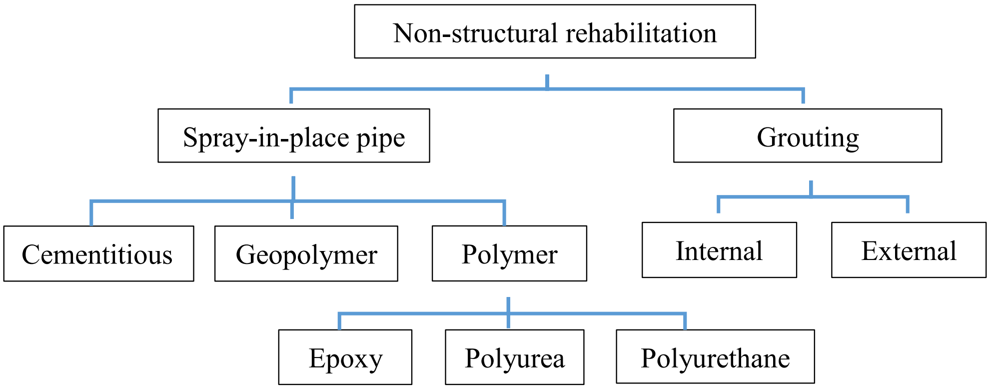
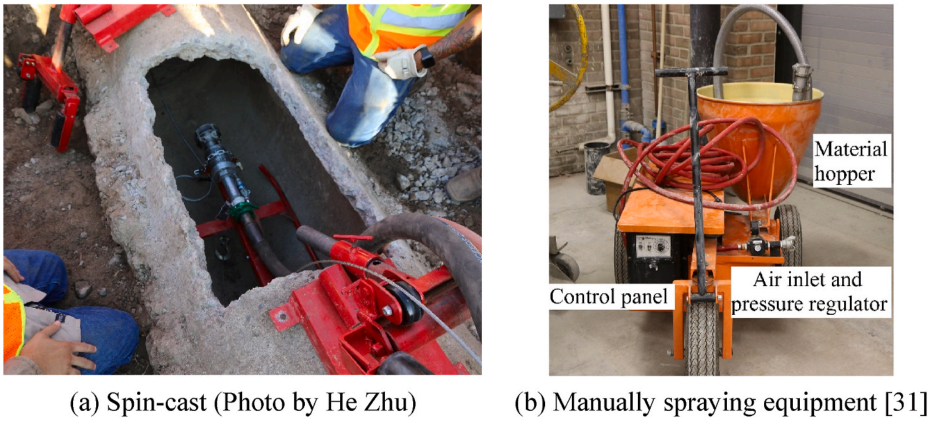


Fig. 1. Non-structural trenchless rehabilitation methods for concrete pipelines.



(a) Spin-cast (Photo by He Zhu) (b) Manually spraying equipment [31]

Fig. 2. Spraying method for pipeline coating.

displacement caused by external loading to the pipeline leads to cracking of cement. Hence, cement-based coating is classified as a non-structural rehabilitation method. Increasing the liner thickness may enhance the structural performance [35,36]. However, the increased thickness reduces the section area and consequently decreases the hydraulic capacity of the pipeline.

Adding fiber reinforcement can improve the structural performance of cementitious materials. Since a pipe liner is a thin shell structure, microfibers are more suitable than macro fibers [37]. Also, steel fibers are not recommended due to corrosion tendency, especially in sewage systems. The fiber restrains the crack opening but does not increase the strength of the cement matrix. Fiber-reinforced mortar also cracks under tensile stress, allowing aggressive fluid penetrating and corroding the host pipe, which accelerates the failure of the repaired pipe. No additional structural stability can be provided if further disintegration occurs [38]. Therefore, considering the complex loading conditions of the water pipe and the uncertainty regarding structural benefits, cement-based coating is categorized as a non-structural rehabilitation method [5,8].

2.1.2. Geopolymer

Geopolymers were developed as a low carbon alternative to Portland cement, the production of which contributes to 5–8% of the total anthropogenic CO_2 emissions [39]. Geopolymer binder is also called alkali-activated cement. Distinct from the cement hydration reaction, geopolymer gains strength by the polycondensation reaction of aluminosilicate with alkalis [40]. Industry byproducts, such as fly ash, clay, metakaolin, silica fume, and slag are common sources of aluminosilicate, while Na/K hydroxide and sodium silicate can act as the alkaline activator as shown in Fig. 3. To facilitate the polymerization process, elevated temperature (mostly above 60 °C [41]) is utilized for curing, leading to a fast strength gain at an early age.

While geopolymers were first invented in the 1970s, they have experienced rapid development for repairing concrete infrastructure [42] and have been commercially available in pipeline rehabilitation since 2011 [43]. The binders of geopolymer from industrial waste, exhibiting up to 70–80 % less carbon emission than ordinary Portland cement (OPC) [27]. The low carbon merit of geopolymer cement has also been demonstrated in pipe rehabilitation [43–45].

Besides the low CO_2 footprint, good mechanical and corrosion-resistant performances are preferred in the water pipe system. The rapid hardening time allows a shorter bypass time than OPC, mitigating the influences of pipe shutdown [44]. The cross-linked structure [41] of geopolymer provides a higher strength, especially higher bonding strengths than OPC, which improves the structural performance of the repaired pipe. Geopolymer improved the structural performance under compression in brick sewer [43] and concrete pipes [6]. However, for the rehabilitation of a cracked pipe, the tensile stress caused by internal pressure or external loading may lead to cracking in the geopolymer liner. The brittle behavior limits the geopolymer, similar to cement to serving as a non-structural repair material.

The high alkali activator dosage adds to the costs of the technology; the cost of geopolymer concrete is estimated as twice that of the OPC-based concrete [44]. The cost is $1300–2000/meter pipe ($400–600/ft) for rehabilitating a 1.5 m diameter sewer pipe [44], which is much higher than the sprayed cement method. Besides, as an emerging technology, the non-availability of long-term durability data may also impede the development of the geopolymer technique in pipelines [40].

2.1.3. Polymer

Polymeric linings are typically based on epoxy, polyurethane,

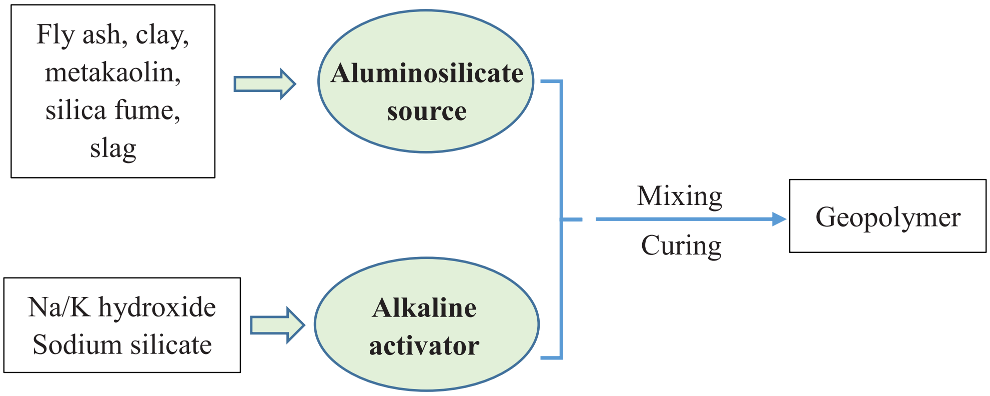


Fig. 3. Schematic diagram of geo-polymerization [27].

polyurea, and their hybrids. All polymeric lining methods require an extensive cleaning of the internal pipe surface, especially for sewage systems. Surface preparation is vital for the integrity and durability of sprayed polymeric linings [8].

The epoxy coating for water pipelines was pioneered in the UK and Japan in the 1980s and was introduced into the U.S. in 1993 [12]. Typically, epoxy products are composed of two components, base and hardener [32]. The curing time may vary from 2 to 16 h, depending on the epoxy type [32], and some may take as long as 14 d [38]. Epoxy has better moisture tolerance when compared to polyurethane and polyurea [5]. The bond strength between epoxy linings and concrete is high enough to resist the hydrostatic forces by infiltration [46]. The lining thickness influences the mechanical performance of the repaired pipe. In one study [47], a 3 mm thick epoxy layer contributes little strength enhancement for the repaired concrete pipe, while a 6 mm thick layer results in a 27 % increase in strength. The increased thickness of epoxy can contribute to the pipe's structural capacity [48]. However, utilizing epoxy for a structural objective is uneconomical because the increased thickness leads to a high material cost. The primary reason for using epoxy lining is to overcome the corrosion problem in both freshwater pipes [32] and sewage systems [7]. Besides, the excellent leak-proof property reduces mineral leaching and associated contamination of water in the pipe [49].

Polyurethane and polyurea linings are both produced using the isocyanate compound while reacting with different resins, e.g., polyol for polyurethane and amine for polyurea (Fig. 4) [38,50]. The curing time is much shorter compared to epoxy and cementitious linings, typically within a matter of minutes for polyurethane and seconds for polyurea, leading to the advantage of fast-return-to-service [51].

Apart from fast curing, the principal benefit of using polyurethane and polyurea is chemical corrosion protection. Polyurethane coating can prolong the service life of the concrete by 14–57 times in a sulfuric acid environment [52]. However, due to the use of isocyanate catalyst, polyurethane, and polyurea liner may release contaminants into the water [53]. Further, extensive ventilation procedures are required for assuring worker safety [5] during coating application. The bonding strength is sensitive to the moisture condition; a damp environment may result in lining collapse [52].

Although a high build thickness of polymeric materials increases the structural strength, it also has disadvantages. First, the high cost may offset the benefits of structural improvement. Second, a thick liner increases the exotherm heat, resulting in localized stress at lining profiles and discontinuities. Finally, the shrinkage of polymeric material during curing may create annular space between the liner and the host pipe, allowing pressurized fluid infiltration leading to liner cracking [54]. Therefore, polymeric linings are classified as a non-structural rehabilitation method.

2.2. Grouting

While the spray-in-place method forms a new liner in the pipe, the grouting technique is usually used for a pipeline that is structurally sound but requires local repair, such as leaking joints, circumferential cracks, and voids in backfill outside the sewer wall. Chemical gel (acrylamide, acrylic, acrylate, and polyurethane-based types), cement, and resin are commonly used grouting materials, which can be applied either by internal grouting or external grouting method [5,30].

2.2.1. Internal grouting

Internal grouting is usually implemented using an inflated sealing packer and a closed-circuit television camera (CCTV) (Fig. 5 (a)). The packer is positioned across the joint using a remote CCTV. The packer is then inflated at its end against the internal surface of the pipe to obtain a sealing effect. Subsequently, the chemical grouting/epoxy resin is injected into the joint using the packer and forced through the joint leak into the surrounding soil. Finally, the leakage defects around the joint are sealed, and the voids in the soil are filled [5,30].

Resin is less toxic than chemical grouting but requires a longer curing time, usually ranging from 24 to 36 h, while chemical grouting hardens within minutes or hours. Unlike resin and chemical grouting (in liquid solution form), cement grout belongs to the suspension grout family [55]. Therefore, cement grout is typically restricted to fill large defects/voids.

Internal grouting is an effective method to reduce the infiltration or exfiltration caused by joint leaking or circumferential cracks. However, it has limitations for repairing pipelines with longitudinal cracks, large settlements, and sinkholes [30]. In addition, the service life is relatively short, usually below 5 years [30].

2.2.2. External grouting

Some external pipe problems, such as subsidence and erosion, lead to drainage pipeline cracking and leakage. Repairing a large settlement with internal grouting is uneconomical, while external grouting is a relatively low-cost and effective method (Fig. 5 (b)). Cement-based and polyurethane grouts are used for external grouting to fill large voids, control seepage, reduce infiltration/exfiltration, and lift the dislodged pipelines [55–57].

The reliability and effectiveness of cement and polyurethane grouting have been affirmed [2]. Moreover, the advantages of polyurethane, such as low weight, high tensile strength, impermeability, and fast construction [56,58,59], are attractive for pipeline repair. However, excess expansion may cause unexpected problems. Notably, the coefficient of thermal expansion of the polyurethane is approximate 866 με/°C (about 100 times that of concrete) [59]. Temperature changes would cause apparent expansion of the solidified polyurethane, leading to

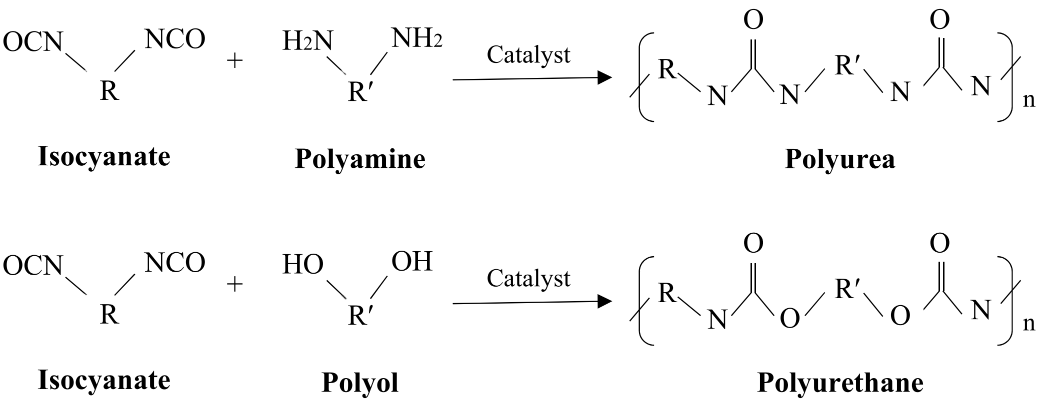
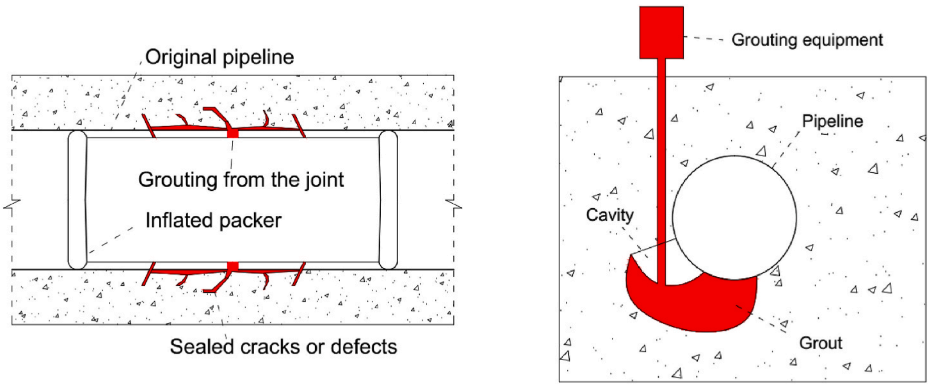


Fig. 4. The chemical reaction of polyurethane and polyurea [50].



(a) Internal grouting [5]. (b) External grouting [2].

Fig. 5. Schematic diagram of the grouting process.

excess uplift and local cracks in concrete pipelines. Therefore, the expansion applied by polyurethane on the concrete pipeline should be controlled carefully in the external grouting process.

3. Semi-structural rehabilitation

Semi-structural rehabilitation (adapted from Refs. [8,30]): Besides corrosion protection and leak control, the new liner works together with the host pipe, resisting the combined effect of internal pressure and external loads. The load capacity of the deteriorated pipe is improved, but still lower compared to the original sound pipe. The semi-structural rehabilitation method includes cure-in-place-pipe (CIPP), close-fit pipe, and fiber-reinforced polymer pipe (FRP).

3.1. Cure-in-place-pipe

3.1.1. CIPP technology and environmental impact

Developed in the 1970s, CIPP has become the dominant liner technology with the largest market share of trenchless rehabilitation methods and remains the most popular method currently [60,61]. A liquid thermoset resin-saturated tube is inserted into the deteriorated pipe by air/water inversion, or mechanically pulling, and then expanded using air/water pressure [5,22]. The inflated tubes with resin are subsequently cured by heat (hot water/steam) or ultraviolet (UV) light to obtain a hardened liner. Based on the curing method, resin type, and tube construction, the CIPP can be summarized as in Fig. 6.

The traditional heat curing method (hot water/steam) adds heat and pressure evenly on the liner, assuring good curing quality of the composited liner [62]. The low cost and the consistently good resulting liner quality promote heat curing as a preferred CIPP curing method. However, the high energy demand and carbon footprints, as well as the requirement of a large area of site access [63], impede the broader application of heat curing [62]. A UV ray curing technology was developed with the advantages of fast curing, high strength development, low carbon footprint, and few chemical emissions [64]. The stiffness and the load capacity of the cured liner are affected by UV light intensity [65]. Inadequate light intensity may result in under-curing or non-uniform curing, and poor strength development. Moreover, the cost of UV curing is higher than that of thermal curing [62].

Due to the merits of copolymerization efficiency, low cost, and wide availability, styrene is the most popular diluent, resulting in an unsaturated polyester generally applicable to CIPP. Vinyl ester and epoxy resins are less frequently utilized because of their higher cost [66]. However, many environmental contamination incidents have been documented and traced to styrene [26], affecting both the water [67] and air [68] quality. In particular, the under-cured resin can release the residue styrene [64]. In addition, other contaminants may be released into the environment during and after the CIPP installation, which requires further investigation concerning pollutant persistence and toxicity [66]. Recently, some states such as California, New York, and Virginia have instituted moratoriums on CIPP use [66].

Styrene-free resin (such as vinyl ester and epoxy) and UV liners have been utilized as environmentally safe resin material [25,69]. Moreover, epoxy resin has superior chemical resistance and a higher strength than polyester resin. However, the high cost of epoxy and vinyl ester resin hinders the wider application of CIPP. Therefore, a cost-effective and eco-friendly CIPP technology is urgently needed.

The tube is mainly utilized for carrying and supporting the resins. The tube is made of non-woven felt (could be reinforced with glass fibers) or woven polyester/glass fiber. With fiber reinforcement, the mechanical performance of the liner is enhanced, suggesting the feasibility of thickness reduction while maintaining the same structural effect

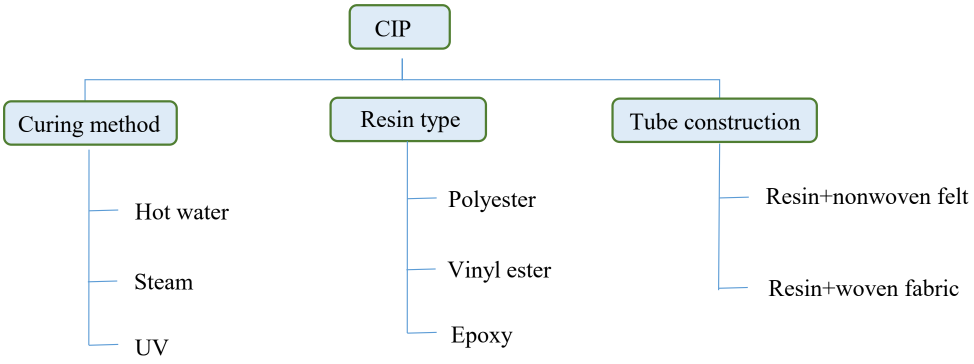


Fig. 6. Classifications of cure-in-place-pipe (CIPP) method [19].

[70]. The decreased thickness has the benefits of increasing the hydraulic capacity of the rehabilitated pipe and decreasing the resin dosage, which further mitigates the environmental concerns [70]. However, since glass fibers may affect the water quality and human health, it is only suitable for drainage pipes [71].

3.1.2. *Structural effect after rehabilitation*

The repaired pipe with CIPP can structurally resist internal pressure, especially when epoxy resin reinforced with glass fibers is used [71]. However, the ability to resist external pressure such as groundwater infiltration, soil pressure, and traffic load remains an important issue. Despite rehabilitation with CIPP, the cracked pipe may still allow groundwater to penetrate the gap between the host pipe and the CIPP liner. ASTM F1216 [16] requires that the CIPP liner possesses resistance to inward buckling or collapse, which has been widely reported in the literature [61]. For pipes subjected to a high hydrostatic pressure, as well as other external loads, the required thickness of CIPP needs to be increased, which sometimes can be impractical [46].

The annular gap between the host pipe and the CIPP liner is inevitable due to the initial ovalization/imperfections of the host pipe, as well as due to resin shrinkage during hardening [72]. The gap reduces the pressure capacity dramatically and results in buckling [73]. One onsite investigation showed that the annular gap between the host pipe and CIPP varied from 0.10 mm to 3.31 mm [74]. In the experimental study of a short-term hydrostatic test, leakages were found, although no buckling occurred [74]. In addition, the long-term performance remains uncertain as sustained loading may reduce the long-term strength and even cause creep failure [75,76]. The host pipe and the CIPP liner with the annular gap work independently under external loading, with little strength enhancement. The pipe and CIPP detach after failure [61].

Adhesion between CIPP and the host pipe can increase the stiffness of the pipe. Furthermore, numerical analysis assuming perfect bonding between liner and pipe shows that CIPP could mitigate the stress and displacement of the pipe under external loading. However, the enhanced stiffness caused by CIPP is insignificant compared to the effect of other factors, such as the corrosion depth and width of the host pipe [77]. The adhesion strength depends on the surface cleanliness, while the realization of a clean surface is a challenging requirement for sewer pipelines.

The long-term performance of CIPP under complex environmental conditions is of concern for engineers [62]. A retrospective evaluation of CIPP rehabilitation of sewers, including flexural strength and modulus (required by Ref. [16]), tensile strength and modulus, porosity, and glass transition temperature was conducted [60,74]. The investigated CIPP liner works in excellent condition even after being in use for 25 years and it is anticipated to have the ability to work for 50 years' lifetime. However, the performance of CIPP depends on the working environment. Long-term exposure to salt and alkaline environments has a detrimental effect on the performance of CIPP liners, in particular for the under-cured CIPP [64]. Moreover, the assessment of the durability of CIPP in an acid environment is rarely reported in the literature and deserves further research.

3.1.3. *Summary of the advantages and challenges of CIPP*

CIPP has the advantages of high efficiency, maintained or improved hydraulic capacity, internal pressure resistance, chemical resistance, and custom-designed capacity [77]. However, CIPP faces many challenges in applications, such as high cost, host pipe applicability (requiring round shape, minor deteriorated state), site access ability, and curing and installation quality (folds, liner peeling, and wrinkles) [25]. Most of the defects, such as wrinkles, bubbles, under-curing, and folds, are created during installation and curing. Strict quality assurance and quality control (QA/QC) may overcome most of those problems, so that CIPP quality control has to be the focus in future research [71]. After CIPP rehabilitation, the host pipe can attain a structural enhancement effect under internal pressure, and a semi-structural enhancement effect under the external load.

3.2. *Close-fit pipe*

The external diameter of the new pipe used in the close-fit pipe matches the inner diameter of the host pipe. Prior to insertion, the close-fit liner is folded in the factory (fold and form (F&F) and deformed and reformed (D&R)) or temporarily deformed at the job site (mechanically folded pipe (MFP) and reduced diameter pipe (RDP)) [78]. Once the new pipe is inserted into the host pipe, the pipe is reverted to its original shape using the thermal form or pressure method. After reversion, the new liner fits snugly with the host pipe called close-fit lining. Polyvinyl chloride (PVC) or polyethylene (PE) pipe are the most used pipe materials [5] for the close-fit method because of their fold-and-form ability, long-term performance of the structure, and chemical resistance, while steel pipe is less used due to its challenge of installation [79].

The close-fit pipe can rehabilitate deteriorated pipelines with structural effects under internal pressure. However, the structural capacity under external load (soil and traffic) remains insufficient. Though the close-fit pipe is designed to tightly fit against the existing pipe, initial lack of fit between the host pipe and liner is inevitable [80] because of the uneven inner surface of the deteriorated pipe, and improper shape of the inserted liner, which has been identified on a site investigation [60]. Groundwater penetration through cracks in the existing pipe can exert pressure onto the liner, increasing the buckling risk of the close-fit liner. Moreover, the annular gap leads to the liner and pipe working independently, where the full slip [81] between liner and host pipe leads to the reduction of resisting compressive thrust capacity [82]. To increase the structural integrity, a form-in-place pipe (FIPP) was developed [78] comprising two thin sheets of HDPE, in which the outer liner is smooth while the inner layer is studded. After installation, the gap between the two layers due to the stud is grouted [5] to form a sandwich structure. The structural integrity is enhanced with a minimum reduction of flow area.

Since the pipe liner is manufactured in a factory, the quality assurance of liner material and installation is higher. Due to the minimal reduction of the flow cross-section as well as the smooth characteristics, the new pipe rehabilitated with the close-fit method may have an enhanced flow capacity. Meanwhile, the PVC/PE liner is capable of installing a jointless pipe with bends up to 45°. The close-fit method has some disadvantages, e.g., the bypass flow requirement increases costs on top of the high cost of the pipe liner. Limited diameter range is available for close-fit pipe, which may not meet the requirement of rehabilitating large-diameter concrete pipes.

3.3. *Fiber-reinforced polymer pipe (FRP)*

3.3.1. *FRP technology for concrete pipe rehabilitation*

FRP is a new type of rehabilitation technology for concrete pipelines, which was first used for the engineering industry in the early 1990s and for strengthening Prestressed Concrete Cylinder Pipes (PCCP) in the late 1990s [83]. The FRP technology has been applied extensively in strengthening civil engineering structures at present [84,85]. Notably, a standard called “AWWA C305-18 CFRP RENEWAL AND STRENGTHENING OF PRESTRESSED CONCRETE CYLINDER PIPE (PCCP)” has been approved by the American Water Works Association in 2018 [86].

FRP is a composite made of polymer reinforced with fibers. Epoxy and polyester are the most adopted resins for FRP applications, of which epoxy has the best mechanical properties but a higher price, while polyester has an inferior mechanical performance but lower costs [28]. Based on the specific requirement, additives such as nano-silica powder can also work in combination with epoxy to improve the performance of the matrix [87].

Glass, carbon, basalt, aramid, and natural fibers are typical reinforcements in FRP [28]. Though glass fibers have the advantages of excellent mechanical properties and moderate cost, broken glass fibers are hazardous to human health, making them unsuitable for water pipelines. Since FRP incorporates 30–70 % by volume of fibers [28], the high cost due to carbon fibers limits the widespread use of FRP in pipeline rehabilitation. Recently, basalt fiber-reinforced polymer (BFRP) has been developed with about 20 % cost of CFRP [88]. However, more layers of BFRP are needed to obtain the same structural effect as CFRP due to the lower strength of BFRP. One natural (jute) fiber has been demonstrated to have comparable strength to the glass fiber [89] concurrent with the advantages of eco-friendly and low cost. However, the natural fibers degrade by swelling in water and shrinking when dried, which weakens the bond between fiber and matrix and decreases the composite strength of FRP [90]. Hence, CFRP is more prevalent than GFRP or BFRP in rehabilitating concrete pipelines in the water field [83].

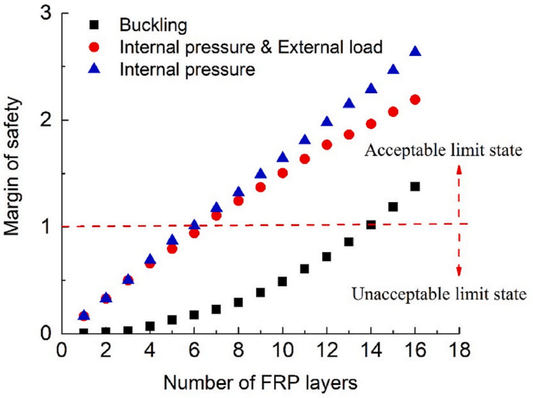
Both external wrapping [91] and internal bonding [92] FRP have been employed to strengthen concrete pipes. External CFRP has primarily been utilized for above-ground pipelines, which cannot be shut down [93]. However, the external bonding method is usually impractical for buried pipes, so the internal bonding method is more prevalent in underground pipe rehabilitation. Internal bonding of FRP onto the host pipe can be realized with the resin transfer molding (RTM) method [94] and manual hand lay-up. Although the RTM method reduces labor costs, problems of internal defects and long resin injection time remain [95]. Consequently, hand lay-up is the preferred method for pipe repair. The terminations of the CFRP liner require attention during installation as leakage is usually observed through delamination [83]. Meanwhile, internal repair with CFRP requires a pipe diameter larger than 750 mm (30-in.) for worker entry. In addition, the safety of workers needs to be assured by proper ventilation and egress especially when operating within a confined space [93].

3.3.2. *Structural effects of FRP rehabilitated pipelines*

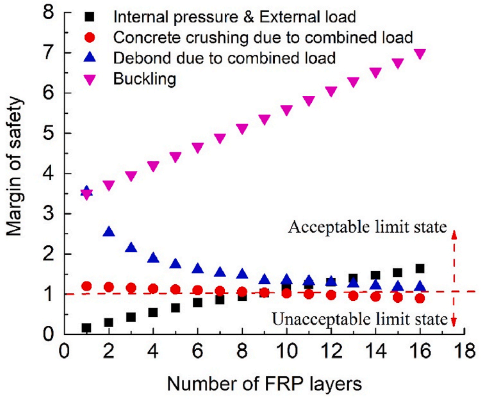
Adhesion between FRP liners and the host pipe is critical [93] for the integrity of the FRP-pipe composite. FRP rehabilitation requires the pipe surface to be thoroughly cleaned and dried before applying the FRP liners. Insufficient surface preparations such as non-circular shape, unsmooth surface with waviness will decrease the strength of the composite significantly [83]. This work also needs skilled workers to ensure the adhesive quality between layers.

The strength of the concrete pipeline suffering from internal pressure can be increased using FRP liners [96]. The strengthening effect depends on the deterioration degree of the concrete pipe and the mechanical properties of FRP liners (layers, strength, and resin type, etc.). For PCCP with steel wire breakage, CFRP works more effectively with increased numbers of broken wires than that with less distressed wires, e.g., the effect of bonded FRP is not significant when the wire breakage rate is 5 % or less [97]. For the host pipe with cracks, the infiltration of underground water decreases the buckling strength of the FRP liner and diminishes the strengthening effect.

From the perspective of material costs, fewer layers of FRP are preferred; however, a limited number of layers decreases the tensile strength of an FRP composite. For example, the repair effect of PCCP with 20 % wire breakage rates bonded with limited layers of FRP was inferior to the unrepaired PCCP with 5 % wire breakage rates [91]. Though more layers can enhance the FRP strength, an optimal layer number exists for pipe-FRP composite strength. In other words, the strengthening effect does not increase with layer number monotonously as expected, e.g., the number of repair layers no longer had a significant effect on concrete once the layer number was larger than four [91]. Furthermore, Lee [97] pointed out that the required layers depend on the deterioration of the host pipe and the loading status (Fig. 7). When FRP works alone due to full deterioration of the host pipe, the minimum required layer number of FRP is 14 (Fig. 7 (a)), while it decreases to 10 layers when FRP and host pipe work together. Further, the required number of layers depends on the internal pressure, external and buckling loads (Fig. 7 (b)).



(a) FRP acts alone as the host pipe fully deteriorates.



(b) FRP works together with the host pipe under different loading limit states.

Fig. 7. The margin of safety (MS) of the repaired pipe with different FRP layers [97].

Fig. 7 reveals that FRP can obtain a structural retrofit effect under internal pressure with limited layers. However, FRP contributes little to resisting external loading. Especially under a crushing test load, almost no contribution by FRP layers can be found [97,98]. Rather than increasing the layer number, a sandwich construction method combining FRP and lightweight honeycomb core was developed [99,100] to increase the stiffness of resisting external loading (Fig. 8). A similar sandwich structure using a hybrid of FRP, steel wire, and resin was also reported in Ref. [101]. FRP is primarily employed as a strengthening method for internal pressure; achieving structural effect for external loading appears impractical. Hence, FRP rehabilitation is classified as a semi-structural method in this study. Due to the high costs of FRP materials and labor, FRP is primarily targeted at structural repairs (such as internal pressure) not suitable using other rehabilitation methods [93].

3.3.3. *Durability of FRP-concrete composite*

As FRP is expected to work for 50 years after rehabilitating a concrete pipe, a time effect factor is adopted in AWWA 305-18 [86] to account for the creep rupture effect under sustained loading. The time effect factor is used for considering the strength reduction due to sustained loading and is designated as 0.60 and 0.80 for service lives of 50 years and 5 years, respectively [103].

Beyond creep rupture, other factors such as wet-dry cycles, medium temperature, and solution types, have a significant influence on the long-term performance of an FRP-concrete composite. Wet-dry salty water cycles decrease the interface bonding of FRP-concrete composite, which is exacerbated under sustained loading [104]. A high temperature accelerates the deterioration of the epoxy and FRP-concrete interface, a chloride [29] medium aggravates the deterioration of FRP, and H_2SO_4

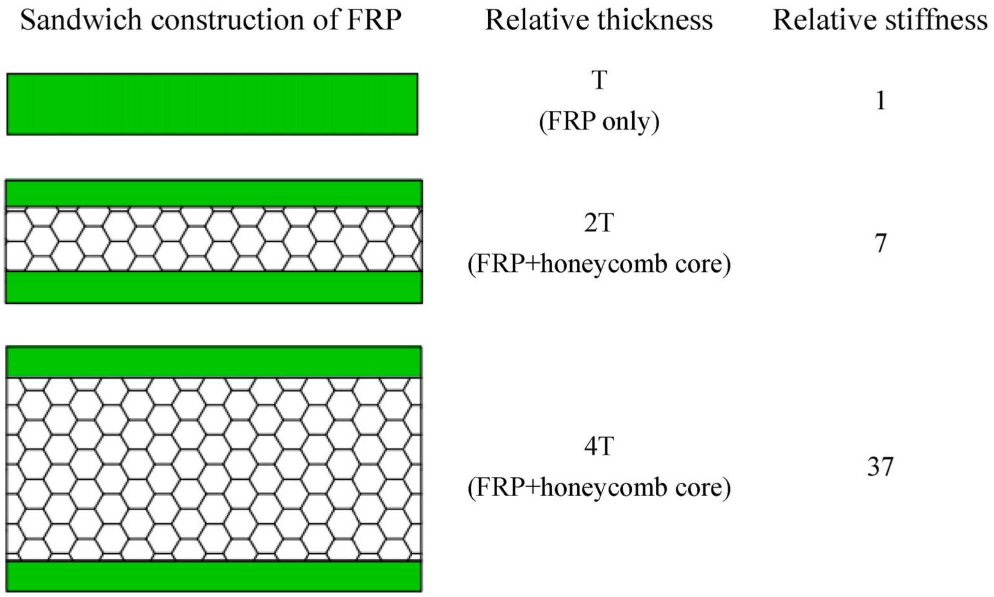


Fig. 8. The sandwich design of FRP construction to increase the total stiffness [102].

attacks both matrix and fiber-matrix interface [105], suggesting potentially more severe damages in the sewer environment. Though the fibers are durable in chloride, alkaline, and acid, the resin is vulnerable in an aggressive environment. The deteriorated resin further decreases the bonding of the fiber-matrix interface. As a result, the FRP-concrete interface is weakened [29]. The durability data of FRP rehabilitated pipelines as relatively new technology is limited, which needs more research and observations.

4. Structural rehabilitation

Structural rehabilitation: The rehabilitated pipe has an enhanced load capacity higher than the original sound pipe under internal pressure and external loading (adapted from Refs. [8,30]). This method includes sliplining (SL) and modified sliplining (MSL).

4.1. Sliplining

4.1.1. Technology and mechanical performance

Sliplining (SL) is one of the earliest rehabilitation methods utilized since the 1940s [5]. A new pipe is inserted into the deteriorated host pipe by pulling or pushing, which requires a working pit for layout. Hence, SL works as a pipe-in-pipe structure. The grout technique is usually applied to fill the annular space between the liner and host pipe to stabilize the liner. The SL liner materials are most commonly manufactured of polyethylene (PE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), GFRP, and corrugated steel pipe (CSP) [24,106,107].

Different from the sprayed cementitious rehabilitation method, SL can increase the load-bearing capacity of the deteriorated concrete pipe. The degree of enhancement depends on the grout (strength and thickness), liner materials, and deteriorated condition of the host pipe. High-strength grout with increased thickness leads to a higher load capacity enhancement [106,108]. However, the higher strength sometimes results in a lower ductility due to the failure of steel reinforcement under high stress [109,110]. The structural integrity is affected by the coupling of the pipe-grout-liner system, which may work as a composite structure or as independent structures depending on the elastic modulus and bond strength of the materials [111]. For example, due to the poor bonding of grout and HDPE liner, the HDPE contributes little to the structural capacity of the rehabilitated concrete pipe, which is mainly contributed by grout [112]. While PVC liner [113] and GFRP liner [114] exhibit the same enhancement as HDPE, the load capacity of CSP is significantly increased because the CSP supports the cracked grout leading to a pseudo-strain-hardening behavior [109,110]. Moreover, the grout penetrates into the cracks on the host pipe, working as an integrated composite structure and increasing the load capacity of the deteriorated pipe.

4.1.2. Advantages and limitations

SL has the critical advantage of creating a new and integral pipe with improved capacity for both internal pressure and external load. In addition, SL can be conducted under live water flow, which saves money and time by avoiding a bypass [115–117]. Due to the excellent corrosion resistance of the SL liner, the pipe-grout-liner system is expected to have good durability with a suggested lifetime of more than 100 years [24]. However, defects have been observed in the field, indicating that comprehensive testing of physical, mechanical, and chemical properties are needed for predicting the lifetime of SL liners [24].

The most significant limitation of SL is the reduction of the pipe section area (usually 10%–30 % [108]), which may not meet the requirement of the hydraulic capacity. In particular, under the backdrop of rapid economic development and the associated increase in water demand and wastewater emission, the loss of flow capacity does not meet the criterion of sustainability. Furthermore, it is challenging to utilize SL for pipes with sharp changes in direction, resulting in additional costs due to the access pit that may be needed. Finally, the cost of SL is comparable to CIPP and higher than other trenchless rehabilitation methods [4].

4.2. Modified sliplining (MSL)

4.2.1. Panel lining

Different from the continuous pipe insertion as SL, the installation of the panel lining (PL) method utilizes pipe segments or panels as a liner so that the SL could be applied for long drive pipe rehabilitation. The pipe liner, mostly fiberglass reinforced polyester [118], is manufactured at a factory, which can be customized for non-circular as well as varying cross-section pipelines. However, PL is limited to rehabilitating sewer pipelines that allow worker-entry and is unsuitable for the rehabilitation of potable water pipelines or pressure pipelines [5]. PL installation can work under restricted flow conditions, which reduces the costs and time associated with bypass.

According to the design purpose, the PL liner is classified as Types I, II, III, and IV [5]. Type I is intended for non-structural rehabilitation such as anti-corrosion or improvement in flow capacity. Type II is designed for carrying an external load of soil or traffic. Type III PL is applied as a standing-alone system that has the ability to resist external hydro pressure. The liner and host pipe may not be bonded together. Combining the advantages of Type II and III, Type IV PL has a fully structural effect with both external load and hydro pressure resistance. The full structural effect is realized by engineering the liner thickness, liner strength, as well as grout thickness and strength.

4.2.2. Spiral wound pipe

To decrease the flow loss of SL and PL methods, a modified sliplining method called spiral wound pipe (SWP) is developed by using PVC-ribbed profiles with interlocking edges [5,8], fed by a winding machine placed in a manhole. The spiral wound liner can be installed against the interior surface of the host pipe or be inserted as a smaller diameter and completed by grouting the annular space [119]. The SWP maintains the advantage of live insertion without bypass, with a minimal reduction in pipe diameter compared to the SL method. However, the load capacity under external load is lower than that for the SL method because of the smaller thickness of grout. In addition, the costs of the SWP are higher compared to the SL [120].

5. Pipeline retrofit with ECC

Pipeline retrofit rehabilitation: In addition to the recovery of the original function of the host pipe, the retrofit leads to enhanced load and deformation capacities with additional function improvements such as self-healing and leak-proof ability. Pipeline retrofit rehabilitation can be realized with an emerging material called Engineered Cementitious Composites (ECC) [21].

5.1. Tailorable ECC for pipe rehabilitation

ECC is a specific fiber reinforced concrete (FRC) designed under the guidance of micromechanical theory, manifesting ultra-high ductility and strain-hardening properties. As a result, ECC is also known as strain-hardening cementitious composites (SHCC). The ultra-high tensile strain capacity (>3 %) is realized by multiple fine micro-cracks, which suppress brittle fracture of concrete. A moderate fiber content (up to 2 % of volume fraction) is sufficient for obtaining the robust strain-hardening performance. Table 1 lists the characteristic parameters of reinforcing fibers, which are commonly used in ECC.

One of the distinctive advantages of ECC is that mechanical performance can be engineered by tailoring the matrix and fibers (Table 2) [21]. The mechanical performance is determined by the synergistic interaction of matrix, fiber, and fiber/matrix interface. PP fibers are usually adopted to develop normal strength ECC (20–55 MPa) with the lowest costs compared to PVA and PE fibers [121,124]. The highest tensile strain-capacity of PP-ECC is reported as 8.9% at a tensile strength of 3.8 MPa. The low tensile strength of PP fibers (850 MPa) does not meet the strain-hardening criterion determined by the micromechanical theory [125] when used in high-strength ECC. PVA fiber can be utilized for medium-strength ECC (30–70 MPa) [126]. By adopting high strength PE fibers, ECC with compressive strength over 200 MPa, and ductility up to 12% has been developed [127–131]. Fig. 9 shows ECC tested under flexural and tensile loading, demonstrating ultra-high ductility and controlled multiple microcracking. While higher performance increases the material costs considerably, the balance of ECC performance and cost could also be obtained with hybrid fibers systems. Hence, the tailorable performance and cost of ECC provide a wide range of design solutions for concrete pipeline rehabilitation.

5.2. Sprayable ECC technology

Beyond the tailorable hardened properties, the fresh state of ECC can also be engineered for different methods of application, such as normal casting, self-consolidating casting, 3D-printing, and spraying [21,31,136]. Spraying would be preferred for pipeline rehabilitation, as introduced in Section 2.1. Although the newly developed ECC has not been applied in concrete pipeline rehabilitation by far, the sprayable ECC has demonstrated effectiveness for other infrastructure repairs [137–141], especially those related to underground and water infrastructures such as irrigation channel [142], tunnel lining [139], dam [143], culvert [144], and water tunnel [21]. These applications have many similarities to concrete pipelines, such as ECC/concrete bonding, underground and wet environments, and annular geometrical shapes, suggesting the feasibility of ECC for concrete pipeline rehabilitation.

A sprayable ECC exhibiting enhanced or comparable mechanical performance to cast ECC has been developed [31]. The sprayed ECC can build up 30–40 mm thickness for overhead spraying at one time without dripping and sloughing (Fig. 10 (a)). Recently, the sprayable ECC has been successfully demonstrated for pipe repair utilizing the centrifugal spraying method (Fig. 10 (b)), which is widely used in cementitious rehabilitated pipelines (Section 2.1, Fig. 2(b)). Fig. 10 (b) shows the centrifugal sprayed ECC with 50 mm built-up thickness at one time evenly and compactly adhering onto the interior surface of the concrete pipe. Hence, ECC sprayability, buildability, and atomization ability (breaking up the ECC at the spray nozzle into small particles for good fiber dispersion and robust strain-hardening behavior) have been experimentally verified for concrete pipe rehabilitation. As reported in Ref. [145], a sewer of 1.5 m diameter and 2740 m length has been rehabilitated with centrifugal sprayed fiber-reinforced concrete, indicating the viability of using centrifugal sprayed ECC for pipelines with various ranges of diameter and length.

5.3. Self-stressing ECC

Conventional trenchless rehabilitation techniques such as SIPP, CIPP, and FRP require extensive surface preparation of the host pipe. This is because the bonding between the host pipe and the repair material is critical to overall performance. The thorough cleaning, as well as surface finishing, increases the construction cost and time. Additionally, surface preparations can be difficult for some pipelines due to the shape ovality, root intrusion, and the severe environment of the sewer. If the host pipe is not properly prepared, the structural effect and the durability of the repaired pipe may be compromised.

Self-stressing material is defined as one that autogenously exerts

Table 1

Technical specifications of synthetic fibers commonly used in ECC.

Fiber type	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Diameter (μm)	Length (mm)	Source
PP	850	6.0	21	12	8–20	[121]
PVA	1600	42.8	6–8	39	8–12	[122]
PE	3000	100	2–3	20–38	8–18	[123]

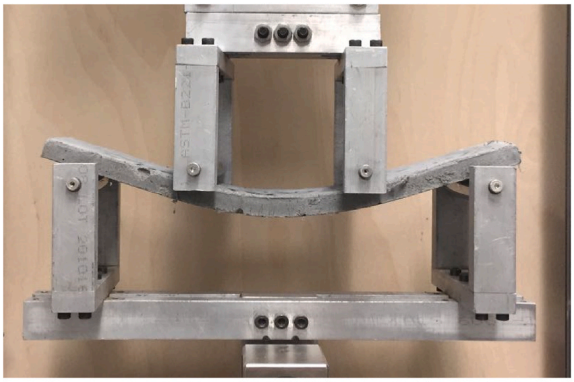
Note.

- Abbreviation: polypropylene (PP), polyvinyl alcohol (PVA), polyethylene (PE).
- The parameters listed above are for the commonly used fibers for ECC. Properties other than those listed above can be found in Ref. [122].

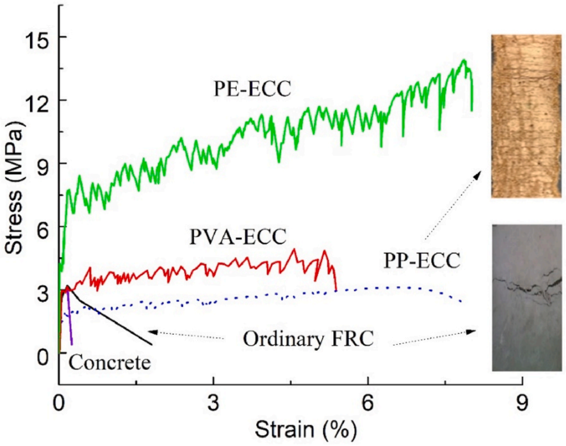
Table 2
The mechanical performance and material cost of typical used ECC.

ECC type	Compressive strength (MPa)	Tensile Strength (MPa)	Tensile strain capacity (%)	Material Cost[a] ($/m^3)	Source
PP-ECC	20–55	2.5-3.8	3–9	167	[121]
PVA-ECC	30–70	3.0–8.0	3–6	178–443	[21,132]
PE-ECC	30–200	3.0–20	3–12	402–643	[123,131,133]

[a] The cost varies depending on the mechanical performance and the cost of fibers.



(a) Bendable ECC sample.



(b) Stress-strain curve under direct tensile test (Data source: FRC [134], PP-ECC [121], PVA-ECC, and concrete [21], PE-ECC [135]), in which PE-ECC and PVA-ECC have a similar crack pattern to PP-ECC shown in the right top insert.

Fig. 9. ECC bending and tensile testing [134,135].

pressure on the repaired structure upon curing. Self-stress is realized by replacing part of ordinary Portland cement (OPC) with calcium sulfoaluminate expansive additive (CSA) [146]. On top of suppressing drying shrinkage, the self-stressing magnitude is designed to generate a moderate expansive stress against the host pipe (Fig. 11).

The self-stressing ECC enhances the integrity of the ECC liner and host pipe. Because of the expansion characteristic, the ECC liner couples seamlessly with the host pipe, and no gap exists. Meanwhile, the shrinkage challenge of cementitious materials is also eliminated. In other words, the problems of shrinkage cracking, annular gap between the new liner and host pipe, and poor adhesion, which remain as challenges in SIPP, CIPP, close-fit, and FRP rehabilitation methods, are overcome when sprayable self-stressing ECC is adopted. The eliminated annular gap further removes any deterioration caused by infiltration and buckling.

The intrinsic expansive characteristic of self-stressing ECC reduces the dependence of the mechanical performance of the rehabilitated pipe on the quality of interface bonding. In fact, it has been demonstrated [140,142] that ECC-concrete composite exhibits better flexural performance under moderate interface bonding than strong bonding, which is different from the traditional concept that strong interface bond results in a higher composite strength. For ECC/concrete composite, a moderate interface bond promotes bifurcation of microcracks from ECC into the composite interface (Fig. 12), thus suppressing brittle fracture of concrete. As a result, the flexural strength and deflection capacity of the ECC-concrete composite is increased due to the strain-hardening contribution of the ductile ECC layer. Therefore, moderate surface preparation to allow sprayed thickness build-up is adequate for self-stressing ECC, exhibiting a distinct advantage over other bond-critical rehabilitation methods.

Beyond the advantage of self-stressing, CSA-based ECC hardens rapidly, leading to the fast returning to service of the rehabilitated pipe. The final setting time of the self-stressing ECC is approximately 3 h [146], comparable to that of shotcrete using accelerators (1–5 h) [159, 160]. When combined with the centrifugal spraying technique, self-stressing ECC considerably improves the construction speed, which is attractive to pipeline owners concerning overall costs related to pipe shutdown and bypass [145].

5.4. Structural and durability performance

5.4.1. Retrofit verification

Concrete pipelines often need to carry live traffic and overburden loads. According to ASTM C497 [147], the external load crushing resistance can be evaluated by the three-edged bearing test (Fig. 13 (a)). For the original sound concrete pipe section used as a control, brittle collapse occurred when the load exceeded the crushing strength (Fig. 13 (c)), as expected. In contrast, the pre-damaged concrete pipe repaired with ECC (Fig. 13 (b)) was able to sustain the applied load Fig. 13 (d) without collapse. Instead, microcracks occurred in the ECC layer of the rehabilitated pipe. The microcracks first appeared in the interior surface of the ECC layer, and multiplied as the load increased. Instead of four macro cracks that fractured the control concrete pipe into four pieces, ductile deformation of the rehabilitated pipe was observed.

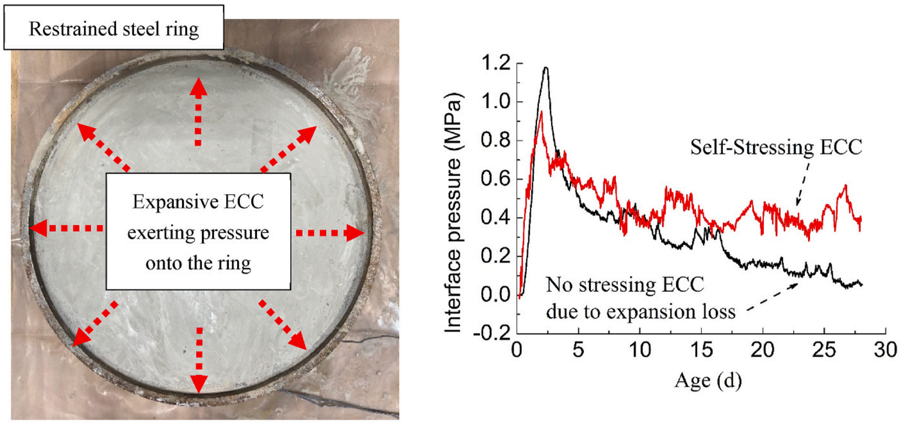
Fig. 14 (a) shows the compression load and displacement result of the crush test (Fig. 13). Both the crushing strength and displacement capacity of the ECC-concrete pipe are higher than those of the original concrete pipe, indicating that the ECC liner structurally retrofits the pre-cracked concrete pipe section. Due to the outstanding ability of crack control, the width of tight cracks in the ECC liner is below 100 μm (in many cases below 50 μm). One ECC-concrete composite pipe of the crush test is terminated when the applied load reached a peak (blue line in Fig. 14 (a)), which is approximately two times the load capacity of the sound concrete pipe. This pipe was further employed for the leakage test (Fig. 14 (b)). Although there are some macro cracks in the host concrete pipe and some micro cracks in ECC liner before filling water, no leakage after 24 h of filled water could be detected, demonstrating the restoration of leakage-proof ability (Fig. 14 (b)).

The retrofit of the ECC lining for the concrete pipeline under internal pressure has also been verified in a water tunnel project [21]. Under the effect of 0.4 MPa design load and 0.28 MPa surge load, the tensile stress is within the first crack strength of ECC, showing that the retrofitted tunnel works at loading in the elastic phase. The total pressure of the water tunnel is also desirable for the pressure requirement of drinking water pipelines [9]. The retrofit effect can be further improved by

(a) Overhead spraying on plywood: 30–40 mm at one time.

(b) Centrifugal sprayed 50 mm thickness of ECC onto a concrete pipe of 300 mm inner diameter.

Fig. 10. Building-up of sprayable ECC [31].



(a) Restrained expansion test.

(b) Interface pressure between the ECC and steel ring.

Fig. 11. The self-stress ECC test (adapted from Ref. [146]).

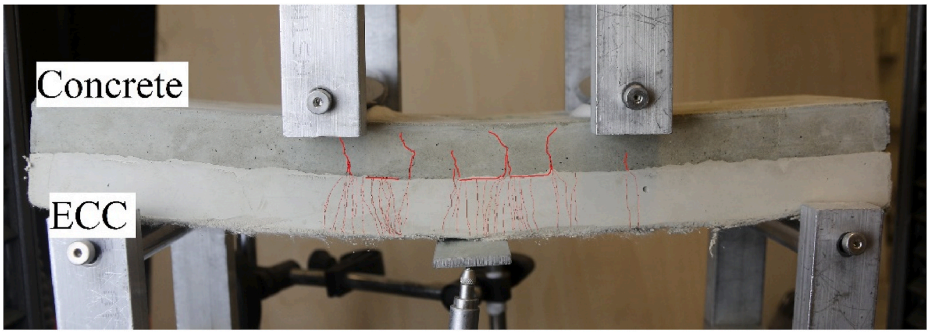


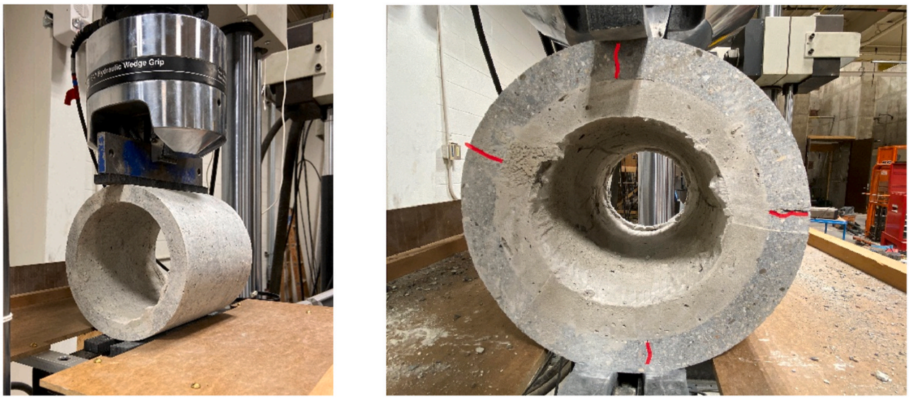
Fig. 12. Ductile failure of ECC-concrete composite under the bending test [31].

increasing the ECC strength and ECC liner thickness, or by utilizing the host pipe residual strength and soil pressure.

5.4.2. Durability performance

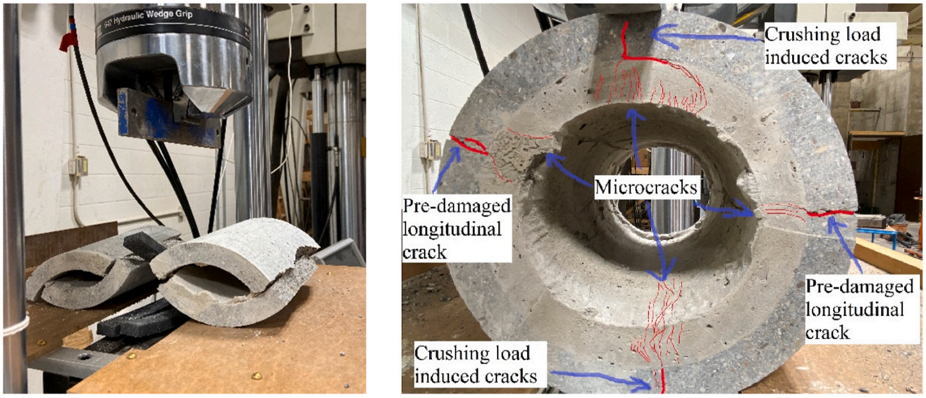
Due to the wet and often aggressive environment in sewage pipelines, the durability of the ECC liner is critical for a long service life of the rehabilitated pipeline. Regarding the characteristics of ECC liner and concrete pipelines, the durability performance of ECC under chemical attack is reviewed from the perspective of fibers, uncracked ECC, and cracked ECC.

The long-term mechanical properties depend on the performance of fiber, matrix, and fiber-matrix bonding. Usually, the strength of the cementitious matrix of ECC will continue to increase with age due to the continued hydration. However, a higher matrix strength and fiber/matrix bond influence the ductility of ECC in different ways depending on the composition. As illustrated in Fig. 15, the tensile strain capacity of PE-ECC increases with age while that of PVA-ECC decreases with age. This is because of the hydrophilic characteristic of PVA fiber, resulting in



(a) Concrete pipe section before crush.

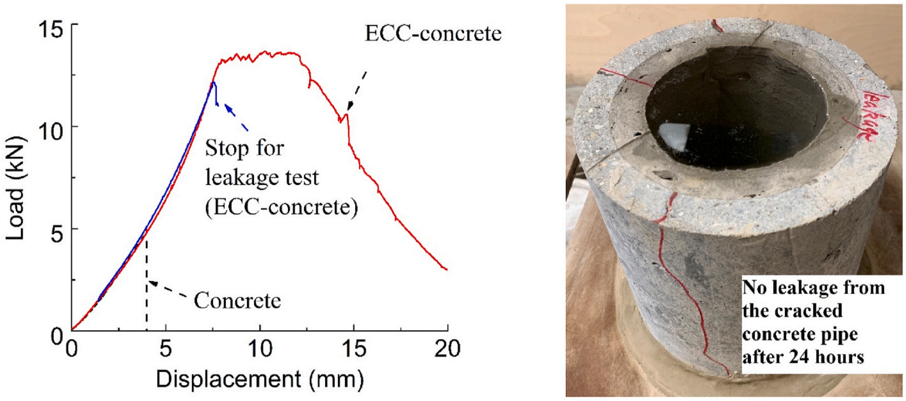
(b) Pre-damaged concrete pipe section repaired with ECC.



(c) Brittle failure of the concrete pipe section.

(d) The ECC-concrete composite exhibits multiple micro-cracks.

Fig. 13. The crush test of the concrete pipe section and ECC-concrete composite pipe section (The ECC layer is manually cast onto the internal surface of concrete with no surface preparation using a tube mold, and then cured in air (20 ± 3 °C, 40 ± 5 % RH) for 28 d. The ECC mix and preparation can be found in Zhu et al. [31]).



(a) Compression load versus the displacement of the crush test.

(b) No leakage from macro cracks of concrete after peak load.

Fig. 14. Demonstration of (a) structural retrofit and (b) leak-proof ability.

an increase of the chemical bonding of the fiber-matrix interface and leading to the fiber rupture rather than pull-out with age. Meanwhile, little chemical bonding exists between the cementitious matrix and the hydrophobic PE fiber. Continued hydration improves the friction between fiber and matrix, resulting in an enhanced tensile strain capacity with age. Though PVA-ECC shows a slight reduction in ductility, the 3 % residual strain capacity remains approximately 300 times that of ordinary concrete, which is adequate for concrete pipe retrofit.

PVA-ECC has been the most widely used and researched in the last 30 years, while PP-ECC and PE-ECC attract increasing attention in recent years. The durability of fibers is vital for ECC durability performance. However, due to limited test results on fiber durability in ECC, the discussion here mainly focuses on the PVA fiber. When exposed to an alkaline environment (cement paste), one study [148] proposes the presence of a threshold temperature of 50 °C, below which no loss of fiber strength can be detected. The temperature in most water pipelines

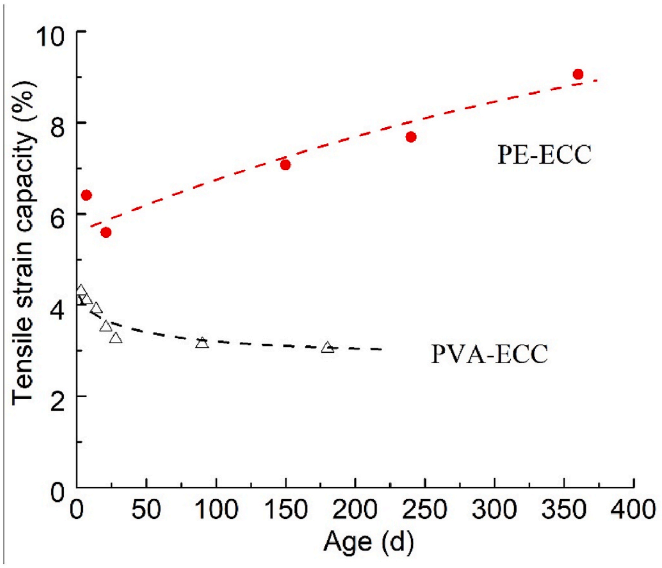


Fig. 15. The long-term tensile strain capacity of ECC (adapted from Ref. [123]).

may be expected to be below this threshold. Apart from the alkaline environment, sewer pipelines may be exposed to acid and organic solvent environments. Accelerated aging tests demonstrated that PVA fiber maintained over 95 % of its strength for over 100 years in acid, alkaline, and organic solvent environment [148].

The durability of steel-reinforced ECC under chemical loading involves two main aspects: first, the effect of chemical agents on the mechanical performance of ECC, in particular, the tensile ductility; and second, the transport of chemical substances into the ECC that leads to steel rebar corrosion. Experimental data suggest that the high ductility combined with inherent tight crack width of ECC enhances the durability of ECC even in aggressive environments, including deicing salt exposure, alkali-silicate reaction, chloride corrosion, alkali penetration, salt freeze-thaw, and sulfate attack [21,123,148–150]. Additionally, ECC exhibits superior performance under an acidic environment [151,152], showing promise for a long service life in pipeline applications.

The most important advantage of ECC is its tight crack width under imposed loads. The finely distributed cracks (width below 50–100 μm) significantly decrease the fluid permeability [153] and diffusivity of aggressive ions. Furthermore, ECC has the inherent ability of self-healing. The products of continued hydration seal the micro-cracks in damaged ECC, further decreasing the permeability of ECC to a level comparable to sound concrete. Moreover, the healed cracks enable the recovery of strength and ductility to a level comparable to or higher than ECC in the undamaged state [154,155].

5.5. *Advantages and limitations of ECC liner*

ECC is a class of ductile cementitious material suitable for use with the SIPP technique, which is one of the oldest methods in pipeline rehabilitation. By adopting a manual or centrifugal spraying method, ECC can be applied for pipes with a range of diameters (worker-entry and no worker-entry) and lengths. The spray process can result in a pipe lining without joints. The expansive characteristic of the ECC liner reduces the need for stringent surface preparation. In addition, the long-term close fit between ECC liner and host pipe eliminates the annular gap, which is commonly observed in other rehabilitation approaches. The rapid hardening property, combined with the centrifugal spray technology, reduces the construction time considerably, further decreases the bypass time and total cost. The tailorable properties (including strength, ductility, crack width, and self-healing ability) of ECC enable the retrofit ability both structural and functional as well as superior durability, exhibiting significant advantages over conventional SIPP, CIPP, SL, close-fit pipe, and FRP liner methods. Finally, the retrofitted ECC-concrete pipeline is more resilient under both static and seismic loads.

ECC also has the advantage of low carbon footprint over concrete. The embodied CO_2 footprint of a low carbon ECC is 90% that of a normal strength concrete (compressive strength 40 MPa) [121]. Further, owing to the superior durable performance of ECC liner, less repair or maintenance is needed for the life cycle, producing less CO_2, and consuming less energy compared to cementitious materials [121,156,157]. The comparison of the life-cycle (embodied and operational) CO_2 footprint between ECC and other rehabilitation methods remains a subject to be studied specifically.

The dry ingredients of ECC can be pre-mixed and pre-packaged in a factory, transported to, and mixed on-site. The application process is almost identical to that of the SIPP with conventional cementitious materials, which requires less labor and specialized equipment at the working site. Hence, the relative low cost of ECC material [121] and reduced construction costs related to bypass time and equipment make sprayable ECC an economically attractive pipeline rehabilitation approach.

Compared to semi-structural rehabilitation methods (CIPP, close-fit, and FRP) which can maintain or slightly enhance the flow capacity, the sprayed ECC method decreases the water flow diameter, especially for structural retrofit with increased lining thickness. Although the thickness requirement for retrofitting concrete pipelines has not been studied, thickness requirement for similar retrofit applications has been established. These include, for example, a 6–10 mm ECC coating for irrigation channels, 20–30 mm ECC coating for masonry walls, and 30–50 mm ECC coating for dams [21,161]. Using 50 mm of ECC for retrofitting a 1000 mm pipe (inner diameter) can decrease 10% of the flow section area, which shows the advantage over structural rehabilitation methods, where 10–30% reduction of the pipe section area is reported [108]. Because the ultra-ductility of ECC suppresses the brittle fracture failure mode, the thickness requirement of ECC is less than sprayed cementitious/geopolymer for the same or better structural performance. This suggests that ECC lowers the reduction of water flow capacity compared to sprayed cementitious/geopolymer method.

The main limitation of sprayable ECC as a pipeline rehabilitation method has to do with its emerging technology nature. There is currently no code or standard established for ECC for pipeline repair. Furthermore, assessments of the mechanical performance and durability of the ECC liner-concrete pipe in the field are not available. More investigations including experimental and numerical analyses, field monitoring, and life-cycle analysis are needed.

A comparison of the advantages and disadvantages of each trenchless rehabilitation method is summarized in Table 3, as well as the "User-friendly" characteristics in Table 4, which can also serve as criteria for method selection.

6. Conclusions

Trenchless rehabilitation methods for concrete pipelines for water are reviewed from the perspective of the structural effect. The rehabilitation approaches are classified as non-structural, semi-structural, structural, and retrofit methods according to the performance of the pipeline under external and internal loading. The following conclusions can be drawn:

- High build thickness of cementitious material or geopolymer can enhance the structural effect of the rehabilitated pipe; however, the vulnerability to cracking due to the brittle material nature can result in the loss of structural capacity. As a result, the spray-in-place method with cementitious or geopolymer materials is mainly utilized for non-structural applications. Due to the high cost of

Table 3
Comparison of the advantages and limitations of trenchless rehabilitation methods for concrete pipelines.

Method	ECC	SIPP			Grout	CIPP	Close-fit	FRP	SL and MSL
		Cementitious	Geopolymer	Polymer					
Integrity of repair	Integral coupling[a]	Gap due to the initial ovalization of lining or imperfections of the host pipe and long-term shrinkage							Need grouting
Surface preparation	Moderate	High requirement							Low
Flexibility of use	Flexible section shape/length range	Flexible diameter: small section/worker-entry				Circular		Circular worker-entry	A large diameter with a flow capacity margin
Bypass	Needed but short	Required							Not needed
Cost[b]	Low	Low	Moderate	High	Moderate	High	Moderate	High	High
Use value	Structural and functional[c] retrofit	Non-structural				Semi-structural for external load Structural (retrofit) for internal pressure			Structural

[a] The integral coupling is realized by expansive and self-stressing ECC.

[b] Each project is unique; therefore, a quantitative comparison of the different methods is difficult to achieve as it depends on many factors (location, repair purpose, technology development with time). The cost is estimated and compared according to Refs. [8,9,12,19,30,158].

[c] Functional refers to leak-proof, self-healing, and corrosion mitigation advantages.

Table 4
"User-friendly" characteristics for the various rehabilitation methods.

Method	ECC	SIPP			Grout	CIPP	Close-fit	FRP[b]	SL	MSL
		Cementitious	Geopolymer[a]	Polymer						
Applicable diameter range (m)	0.3–5.0[c]			0.1–4.5	varies	0.1–2.7	0.1–1.6	0.75–5.0	0.3–4.0	0.2–3.5
Maximum length of application (m)	2700[c]			300	Local repair	914	300	Limited by costs	300	300
Recommended thickness (mm)	10–50	6–13	12.5–37.5	1–5		3–50	5–30	<10 layers	Pipe thickness plus grout thickness	
Tolerable pipe bend	No limitation for manual spraying, while the pipeline with bend should allow the spinner to be towed for centrifugal spraying.					Up to 90°[e]	45°	No limitation	No bend	No limitation
Change in diameter along its length acceptable?	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes
Curing time (h)	1–5		0.25–3	0.1–20	0.1–10	1–5	Not needed	2–10	Grout curing>10	
Speed of application[d]	Fast				Moderate	Fast	Moderate	Low	Moderate	Moderate

Note: Other characteristics in Table 4 are summarized from [4,5,9].

[a] Data from Ref. [27].

[b] Data from Ref. [97].

[c] Maximum applicable diameter (5.0 m) and maximum length of application have been demonstrated by the centrifugal spray method [145]. The manually/robotized spray method is suitable for still larger diameter pipelines.

[d] Speed of application differs among projects such as the degree of deterioration of the host pipe, non-structural/semi-structural/structural/retrofit requirement. Hence the speed of application is compared relatively for the different methods, rather than quantitatively.

[e] Tolerable pipe bend depends on the installation and curing processes of the various systems. CIPP liners by inverted insertion can negotiate bends up to 90° [5].

polymers, the spray-in-place with polymer is primarily used for anti-leakage and anti-corrosion purposes, rather than for structural enhancement.

- Cure-in-place-pipe (CIPP) can achieve enhanced structural integrity under internal pressure, but only a semi-structural effect under external loading can be considered due to its low stiffness. CIPP has the advantages of high construction efficiency, maintained/enhanced hydraulic capacity, and chemical resistance. However, high cost, host pipe requirement (round shape, minor deterioration), and defects caused by installation and curing limit those advantages. The strict quality assurance, quality control, and the long-term performance of CIPP require closer examination.
- The close-fit method inserts a new pipe fitting snugly to the host pipe to obtain a minimum hydraulic capacity loss or better flow capacity. The annular gap between the liner and host pipe is inevitable due to uneven pipe surface and shrinkage of the inserted liner. The annular gap decreases the buckling resistance under external pressure caused by underground water.
- Due to high cost, FRP is primarily adopted in projects when other methods are not feasible, such as in the rehabilitation of prestressed concrete pipe under high internal pressure. The structural enhancement is determined by the synergy effect of layer numbers and bonding between layers. However, more FRP layers do not contribute to a higher load-bearing capacity due to the low stiffness of the FRP layer.
- Sliplining and modified sliplining involve inserting a new pipe (liner) into the host pipe, with the advantage of allowing live water flow during installation. The grouted gap between the host pipe and liner leads to structure rehabilitation. However, the reduction of the pipe section significantly decreases the flow capacity, impeding the wider application of this method.
- ECC provides both structural and functional retrofit for concrete pipelines, benefitting from its ultra-high ductility, tailorable mechanical performance, and finely distributed microcracks. The demonstrated improvement of load capacity, leak-proof ability (micro-cracks and self-healing), and enhanced integrity (expansive coupling) promote ECC as a promising sustainable and resilient material for concrete pipeline retrofit.

Long-term performance data of rehabilitated pipelines relevant to service life and performance design remain limited. Additionally, life-cycle analysis, such as cost, repair frequency, CO_2 emission, and energy consumption, attracts increasing attention from a sustainability viewpoint. Sustainability may be another criterion for the method selection of pipe rehabilitation. The use of self-stressing ECC in pipeline rehabilitation is just getting started. More in-depth understanding of the mechanical performance and durability of ECC-concrete pipe composite, as well as life-cycle analysis, are needed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is partially supported by the E.B. Wylie Collegiate Chair Professorship in Civil and Environmental Engineering of the University of Michigan. The authors thank Kristian Loevlie, Shotcrete Technologies, Inc., for the assistance of onsite application of the centrifugal spraying technique.

References

[1] J.W. Heidrick, M.S. Mihm, Pipelines 2019: Condition Assessment, Construction, and Rehabilitation, ASCE, Reston, VA, 2019.
[2] H. Fang, B. Li, F. Wang, Y. Wang, C. Cui, The mechanical behaviour of drainage pipeline under traffic load before and after polymer grouting trenchless repairing, Tunn. Undergr. Space Technol. 74 (2018) 185–194.
[3] ASCE, 2021 Infrastructure Report Card, ASCE, Reston, VA, 2021.
[4] A. Selvakumar, A.N. Tafuri, R. Morrison, R. Sterling, State of technology for renewal of sewer force mains, Urban Water J. 8 (2011) 279–292.
[5] M. Najafi, S.B. Gokhale, Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal, McGraw-Hill, New York, 2014.
[6] N. Roghanian, N. Banthia, Development of a sustainable coating and repair material to prevent bio-corrosion in concrete sewer and waste-water pipes, Cement Concr. Compos. 100 (2019) 99–107.
[7] A. Selvakumar, A.N. Tafuri, Rehabilitation of aging water infrastructure systems: key challenges and issues, J. Infrastruct. Syst. 18 (2012) 202–209.
[8] A.W.W.A. AWWA, in: Manual M28: Rehabilitation of Water Mains, third ed., American Water Works Association, Denver, CO, 2014.
[9] A. Selvakumar, R. Morrison, T. Sangster, D. Downey, J. Matthews, W. Condit, S. Sinha, S. Maniar, R. Sterling, H.N. Aaron, State of Technology for Rehabilitation of Water Distribution Systems, U.S. Environmental Protection Agency, Washington, DC, 2013.
[10] C. Garcia, D.M. Abraham, S. Gokhale, T. Iseley, Rehabilitation alternatives for concrete and brick sewers, Pract. Period. Struct. Des. Construct. 7 (2002) 164–173.
[11] H. Zhu, Y. Hu, Q. Li, R. Ma, Restrained cracking failure behavior of concrete due to temperature and shrinkage, Construct. Build. Mater. 244 (2020) 118318.
[12] A.A. Jain, Evaluation of Trenchless Renewal Methods for Potable Water Distribution Pipes, THE UNIVERSITY OF TEXAS AT ARLINGTON, ARLINGTON, 2011.
[13] M. O'Connell, C. McNally, M.G. Richardson, Biochemical attack on concrete in wastewater applications: a state of the art review, Cement Concr. Compos. 32 (2010) 479–485.
[14] T. Wang, L. Tan, S. Xie, B. Ma, Development and applications of common utility tunnels in China, Tunn. Undergr. Space Technol. 76 (2018) 92–106.
[15] M. Malek Mohammadi, M. Najafi, V. Kaushal, R. Serajiantehrani, N. Salehabadi, T. Ashoori, Sewer pipes condition prediction models: a state-of-the-art review, Infrastructure 4 (2019) 64.
[16] ASTM F1216-16, Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube, ASTM International, West Conshohocken, PA, 2016.
[17] B. Ma, M. Najafi, Development and applications of trenchless technology in China, Tunn. Undergr. Space Technol. 23 (2008) 476–480.
[18] M.R. Zare, D.T. Iseley, M. Najafi, Trenchless limitations on postearthquake repair and rehabilitation of unpressurized networks: christchurch, New Zealand, J. Pipeline Syst. Eng. Pract. 10 (2019), 05019002.
[19] H. Lu, S. Behbahani, M. Azimi, J.C. Matthews, S. Han, T. Iseley, Trenchless construction Technologies for oil and gas pipelines: state-of-the-art review, J. Construct. Eng. Manag. 146 (2020), 03120001.
[20] T. Elwira, Z. Aleksandra, Example of sewerage system rehabilitation using trenchless technology, Ecol. Chem. Eng. 24 (2017) 405.
[21] V.C. Li, Engineered Cementitious Composites (ECC): Bendable Concrete for Sustainable and Resilient Infrastructure, Springer, 2019.
[22] J.C. Matthews, A. Selvakumar, W. Condit, Current and emerging water main renewal Technologies, J. Infrastruct. Syst. 19 (2013) 231–241.
[23] V. Kaushal, M. Najafi, J. Love, S.R. Qasim, Microbiologically induced deterioration and protection of concrete in municipal sewerage system: technical review, J. Pipeline Syst. Eng. Pract. 11 (2020).
[24] K.F. Makris, J. Langeveld, F.H.L.R. Clemens, A review on the durability of PVC sewer pipes: research vs. practice, Struct. Insfrastruct. Eng. 16 (2020) 880–897.
[25] S. Das, A. Bayat, L. Gay, M. Salimi, J. Matthews, A comprehensive review on the challenges of cured-in-place pipe (CIPP) installations, J. Water Supply Res. Technol. - Aqua 65 (2016) 583–596.
[26] V. Kaushal, M. Najafi, M. Sattler, K. Schug, Review of literature on chemical emissions and worker exposures associated with cured-in-place pipe (CIPP) installation, Pipelines 2019: Multidisc. Topics Utility Eng. Survey. (2019) 565–573.
[27] G.F. Huseien, J. Mirza, M. Ismail, S.K. Ghoshal, A.A. Hussein, Geopolymer mortars as sustainable repair material: a comprehensive review, Renew. Sustain. Energy Rev. 80 (2017) 54–74.
[28] L. Cercone, J.D. Lockwood, Review of FRP composite materials for pipeline repair, Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy (2005) 1001–1013.
[29] J. Li, J. Xie, F. Liu, Z. Lu, A critical review and assessment for FRP-concrete bond systems with epoxy resin exposed to chloride environments, Compos. Struct. 229 (2019) 111372.
[30] A. Selvakumar, R. Sterling, J. Simicevic, E. Allouche, W. Condit, L. Wang, State of Technology for Rehabilitation of Wastewater Collection Systems, US Environmental Protection Agency, Washington, DC, 2010. EPA/600/R-10/078.
[31] H. Zhu, K. Yu, V.C. Li, Sprayable engineered cementitious composites (ECC) using calcined clay limestone cement (LC3) and PP fiber, Cement Concr. Compos. 115 (2021) 103868.
[32] S.G. Motlagh, A. Jain, M. Najafi, Comparison of spray-on linings for water pipeline renewal applications, Pipelines 2013: Pipelines and Trenchless Construction and Renewals—A Global Perspective (2013) 1113–1125.
[33] K.E. Kurtis, K. Shomglin, P.J.M. Monteiro, J. Harvey, J. Roesler, Accelerated test for measuring sulfate resistance of calcium sulfoaluminate, calcium aluminate, and Portland cements, J. Mater. Civ. Eng. 13 (2001) 216–221.
[34] S. Wisotzkey, H. Carr, E. Fyfe, An automated repair method of water pipe infrastructure using carbon fiber bundles, in: Proceedings of SPIE, SPIE-INT SOC OPTICAL ENGINEERING, BELLINGHAM, 2011.
[35] D. Becerril García, I.D. Moore, Performance of deteriorated corrugated steel culverts rehabilitated with sprayed-on cementitious liners subjected to surface loads, Tunn. Undergr. Space Technol. 47 (2015) 222–232.
[36] I.D. Moore, D.B. García, Ultimate strength testing of two deteriorated metal culverts repaired with spray-on cementitious liners, Transport. Res. Rec. 2522 (2015) 139–147.
[37] Z.K. Kouchesfehani, A.D. Tehrani, M. Najafi, J.E. Syar, E. Kampbell, Adding additional reinforcement to improve the structural performance of spray applied pipe lining rehabilitation technology: a review, 2019, Pipelines (2019) 10–23.
[38] E.J. Steward, E.N. Allouche, M.E. Baumert, J. Gordon, Testing of rigid polyurethane spray-on lining under internal pressure, 2009, Pipelines (2009) 751–764.
[39] Y.C. Díaz, S.S. Berriel, U. Heierli, A.R. Favier, I.R.S. Machado, K.L. Scrivener, J.F. M. Hernández, G. Habert, Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies, Dev. Eng. 2 (2017) 82–91.
[40] N.B. Singh, B. Middendorf, Geopolymers as an alternative to Portland cement: an overview, Construct. Build. Mater. 237 (2020) 117455.
[41] C. Montes, E.N. Allouche, Evaluation of the potential of geopolymer mortar in the rehabilitation of buried infrastructure, Struct. Insfrastruct. Eng. 8 (2012) 89–98.
[42] F. Pacheco-Torgal, Z. Abdollahnejad, S. Miraldo, S. Baklouti, Y. Ding, An overview on the potential of geopolymers for concrete infrastructure rehabilitation, Construct. Build. Mater. 36 (2012) 1053–1058.
[43] M. Goulet, S. Naiva, J. Fleming, Narragansett bay commission rehabilitation of large diameter brick sewer with geopolymer mortar, 2019, Pipelines (2019) 233–247.
[44] A. Selvakumar, J.C. Matthews, Demonstration and evaluation of innovative rehabilitation Technologies for water infrastructure systems, J. Pipeline Syst. Eng. Pract. 8 (2017).
[45] S. Bian, S. Naiva, T. Bako, DC Water New Jersey B Street 12-To-18-Foot Diameter Trunk Sewer Geopolymer Rehabilitation during Live Dry Weather Flow, Pipelines 2019, Condition Assessment, Construction, and Rehabilitation, ASCE, Reston, VA, 2019, pp. 127–139.
[46] K.A. Harries, M. Sweriduk, D. Warren, Performance of spray-applied epoxy lining system subject to infiltration, in: Tunnelling and Underground Space Technology incorporating Trenchless Technology Research 43, 2014, pp. 389–397.
[47] E. Riahi, X. Yu, M. Najafi, V.F. Sever, D-load strength of concrete pipes with epoxy linings, J. Pipeline Syst. Eng. Pract. 10 (2019) 4019030.
[48] X. Yu, E. Riahi, A. Entezarmahdi, M. Najafi, V.F. Sever, Experimental and numerical analyses of strength of epoxy-coated concrete under different load configurations, J. Pipeline Syst. Eng. Pract. 7 (2016), 04015024.
[49] C. Grella, I.A. Wright, S.J. Findlay, O.J. Jonasson, Geochemical contamination of urban water by concrete stormwater infrastructure: applying an epoxy resin coating as a control treatment, Urban Water J. 13 (2016) 212–219.
[50] D. Primeaux, Polyurea vs. Polyurethane & polyurethane/polyurea: what's the difference, in: Proceedings of the Polyurea Linings Annual Conference, Polyurea Development Assocaition (PDA), Tampa, FL, USA, 2004, pp. 2–4.
[51] S.K. Ha, H.K. Lee, I.S. Kang, Structural behavior and performance of water pipes rehabilitated with a fast-setting polyurea–urethane lining, in: Tunnelling and

Underground Space Technology incorporating Trenchless Technology Research 52, 2016, pp. 192–201.
[52] C. Vipulanandan, J. Liu, Performance of polyurethane-coated concrete in sewer environment, Cement Concr. Res. 35 (2005) 1754–1763.
[53] B.M. Donaldson, A.J. Whelton, Water Quality Implications of Culvert Repair Options: Cementitious and Polyurea Spray-On Liners, Virginia Center for Transportation Innovation and Research, 2012.
[54] K. Weisenberg, T. Iseley, L. Li, Spray in place pipe (SIPP): materials composite and implementation methodology for surviving pressure pipe failure, 2018, Pipelines (2018) 417–422.
[55] A. Naudts, Irreversible Changes in the Grouting Industry Caused by Polyurethane Grouting: an Overview of 30 Years of Polyurethane Grouting, Grouting and Ground Treatment, 2003, pp. 1266–1280.
[56] R. Wang, F. Wang, J. Xu, Y. Zhong, S. Li, Full-scale experimental study of the dynamic performance of buried drainage pipes under polymer grouting trenchless rehabilitation, Ocean Eng. 181 (2019) 121–133.
[57] Z. Zhang, H. Fang, B. Li, Mechanical properties of concrete pipes with pre-existing cracks, Appl. Sci. 10 (2020) 1545.
[58] Y. Wei, F. Wang, X. Gao, Y. Zhong, Microstructure and fatigue performance of polyurethane grout materials under compression, J. Mater. Civ. Eng. 29 (2017), 04017101.
[59] M. Shi, F. Wang, J. Luo, Compressive strength of polymer grouting material at different temperatures, J. Wuhan Univ. Technol.-Materials Sci. Ed. 25 (2010) 962–965.
[60] S. Alam, R.L. Sterling, E. Allouche, W. Condit, J. Matthews, A. Selvakumar, J. Simicevic, A retrospective evaluation of the performance of liner systems used to rehabilitate municipal gravity sewers, Tunn. Undergr. Space Technol. 50 (2015) 451–464.
[61] K.A. Mogielski, A. Kuliczkowski, E. Kuliczkowska, Change in toughness parameters of sewer pipes rehabilitated with two types of epoxy CIPP liners, J. Pipeline Syst. Eng. Pract. 8 (2017), 04017015.
[62] H.W. Ji, D.D. Koo, J. Kang, Short- and long-term structural characterization of cured-in-place pipe liner with reinforced glass fiber material, Int. J. Environ. Res. Publ. Health 17 (2020) 2073.
[63] J.C. Matthews, Large-diameter sewer rehabilitation using a fiber-reinforced cured-in-place pipe, Pract. Period. Struct. Des. Construct. 20 (2015).
[64] M. Nuruddin, K. DeCocker, S.M.T. Sendesi, A.J. Whelton, J.P. Youngblood, J. A. Howarter, Influence of aggressive environmental aging on mechanical and thermo-mechanical properties of Ultra Violet (UV) Cured in Place Pipe liners, J. Compos. Mater. 54 (23) (2020) 3365–3370.
[65] J.A. Peck, G. Li, S. Pang, M.A. Stubblefield, Light intensity effect on UV cured FRP coupled composite pipe joints, Compos. Struct. 64 (2004) 539–546.
[66] M.L. Tabor, D. Newman, A.J. Whelton, Stormwater chemical contamination caused by cured-in-place pipe (CIPP) infrastructure rehabilitation activities, Environ. Sci. Technol. 48 (2014) 10938–10947.
[67] B.M. Donaldson, in: C.F.T.I. Virginia (Ed.), Water Quality Implications of Culvert Repair Options: Vinyl Ester Based and Ultraviolet Cured-In-Place Pipe Liners, 2012.
[68] K. Ra, S.M. Teimouri Sendesi, M. Nuruddin, N.N. Zyaykina, E.N. Conkling, B. E. Boor, C.T. Jafvert, J.A. Howarter, J.P. Youngblood, A.J. Whelton, Considerations for emission monitoring and liner analysis of thermally manufactured sewer cured-in-place-pipes (CIPP), J. Hazard Mater. 371 (2019) 540–549.
[69] A. Parka, E. Kuliczkowska, A. Kuliczkowski, A. Zwierzchowska, Selection of pressure linings used for trenchless renovation of water pipelines, Tunn. Undergr. Space Technol. 98 (2020).
[70] H.W. Ji, S.S. Yoo, J. Kim, D.D. Koo, The mechanical properties of high strength reinforced cured-in-place pipe (CIPP) liner composites for urban water infrastructure rehabilitation, Water 10 (2018) 103218.
[71] D. Yan, R. Wang, S. Zhang, X. Yin, Development and research of fiber reinforced composites for CIPP for pipeline rehabilitation, ICPTT 2013: trenchless technology - the best choice for underground pipeline construction and renewal, in: Proceedings of the International Conference on Pipelines and Trenchless Technology, 2013, pp. 731–737.
[72] G. Bontus, R. Kodadek, M.J. Caputi, R. Baxter, I.A. Lancaster, Qualitative assessment of mechanical and adhesive service connections for CIPP, 2018, Pipelines (2018) 454–463.
[73] Z. Li, F. Tang, Y. Chen, X. Zou, Stability of the pipe-liner system with a grouting void surrounded by the saturated soil, Eng. Struct. 196 (2019) 109284.
[74] E. Allouche, S. Alam, J. Simicevic, R. Sterling, W. Condit, J. Matthews, A. Selvakumar, A pilot study for retrospective evaluation of cured-in-place pipe (CIPP) rehabilitation of municipal gravity sewers, Tunn. Undergr. Space Technol. 39 (2014) 82–93.
[75] H. Zhu, Q. Li, R. Ma, L. Yang, Y. Hu, J. Zhang, Water-repellent additive that increases concrete cracking resistance in dry curing environments, Construct. Build. Mater. 249 (2020) 118704.
[76] R. Nassar, M. Yousef, Analysis of creep failure times of cured-in-place pipe rehabilitation liners, Tunn. Undergr. Space Technol. 17 (2002) 327–332.
[77] H. Fang, K. Yang, B. Li, H. He, B. Xue, S. Georgantzinos, Parameter analysis of wall thickness of cured-in-place pipe linings for semistructured rehabilitation of concrete drainage pipe, Math. Probl Eng. 2020 (2020) 5271027.
[78] M. Hastak, S. Gokhale, System for evaluating underground pipeline renewal options, J. Infrastruct. Syst. 6 (2000) 105–113.
[79] W. Zhou, C. Li, B. Ma, M. Najafi, Buckling strength of a thin-wall stainless steel liner used to rehabilitate water supply pipelines, J. Pipeline Syst. Eng. Pract. 7 (2016), 04015017.
[80] V.F. Sever, R.M. Bakeer, Annular flow in lined pipelines, 2009, Pipelines (2009) 741–750.
[81] T.C.M. Law, I.D. Moore, Numerical modeling of tight fitting flexible liner in damaged sewer under earth loads, Tunn. Undergr. Space Technol. 22 (2007) 655–665.
[82] T.C. Law, I.D. Moore, Response of repaired sewers under earthloads, Transport. Res. Rec. 1845 (2003) 173–181.
[83] M.S. Zarghamee, AWWA C305—A New Standard for CFRP Renewal and Strengthening of PCCP, Pipelines 2019: Condition Assessment, Construction, and Rehabilitation, American Society of Civil Engineers, Reston, VA, 2019, pp. 535–544.
[84] V.M. Karbhari, Rehabilitation of Pipelines Using Fibre Reinforced Polymer (FRP) Composites, Elsevier Science & Technology, Cambridge, 2015.
[85] J. Bai, Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications, Elsevier, 2013.
[86] AWWA, AWWA C305-18 CFRP RENEWAL AND STRENGTHENING OF PRESTRESSED CONCRETE CYLINDER PIPE, PCCP), New York, 2018.
[87] Y. Li, X. Liu, J. Li, Experimental study of retrofitted cracked concrete with FRP and nanomodified epoxy resin, J. Mater. Civ. Eng. 29 (2017), 04016275.
[88] S. Jayasuriya, B. Chegeni, S. Das, Use of BFRP wrap for rehabilitation of pipeline in bending with various corrosion depths, J. Pipeline Syst. Eng. Pract. 11 (2020), 04019038.
[89] H.N. Yu, S.S. Kim, I.U. Hwang, D.G. Lee, Application of natural fiber reinforced composites to trenchless rehabilitation of underground pipes, Compos. Struct. 86 (2008) 285–290.
[90] R. Kumar, M.I. Ul Haq, A. Raina, A. Anand, Industrial applications of natural fibre-reinforced polymer composites – challenges and opportunities, Int. J. Sustain. Eng. 12 (2019) 212–220.
[91] K. Zhai, H. Fang, B. Fu, F. Wang, B. Hu, Mechanical response of externally bonded CFRP on repair of PCCPs with broken wires under internal water pressure, Construct. Build. Mater. 239 (2020) 117878.
[92] H. Hu, T. Dou, F. Niu, H. Zhang, W. Su, Experimental and numerical study on CFRP-lined prestressed concrete cylinder pipe under internal pressure, Eng. Struct. 190 (2019) 480–492.
[93] A.B. Pridmore, R.P. Ojdrovic, in: Types of Pipe Repaired with Composites: Water Supply and Sewage Pipelines, Rehabilitation of Pipelines Using Fiber-Reinforced Polymer (FRP) Composites, Woodhead Publishing, 2015, pp. 1–15.
[94] W.S. Chin, D.G. Lee, Development of the trenchless rehabilitation process for underground pipes based on RTM, Compos. Struct. 68 (2005) 267–283.
[95] D.G. Lee, W.S. Chin, J.W. Kwon, A.K. Yoo, Repair of underground buried pipes with resin transfer molding, Compos. Struct. 57 (2002) 67–77.
[96] D.C. Lee, V.M. Karbhari, Rehabilitation of large diameter prestressed cylinder concrete pipe (PCCP) with FRP composites — experimental investigation, Adv. Struct. Eng. 8 (2005) 31–44.
[97] L. Yongjei, L. Eun-Taik, Retrofit design of damaged prestressed concrete cylinder pipes, Int. J. Concr. Struct. Mater. 7 (2013) 265–271.
[98] A.S. Kanagaraj, FRP Materials for Rehabilitation of Buried Pipes, 7th International Conference on Engineering Mechanics and Materials, Laval, QC, Canada, Canadian Society for Civil Engineering (CSCE), 2019, pp. 1–10.
[99] M. Ehsani, ASCE innovation award winner: sandwich construction carbon FRP pipe, Pipelines 2017 (2017) 10–25.
[100] V.F. Sever, M. Ehsani, Designing an Economical FRP System for Pipeline Rehabilitation, AMER SOC CIVIL ENGINEERS, NEW YORK, 2019, pp. 117–124.
[101] L. Aguiar, A. Pridmore, M. Geraghty, Miami-dade implements hybrid FRP trenchless repair system, 2015, Pipelines (2015) 1257–1267.
[102] M. Ehsani, Introducing a new honeycomb-FRP pipe, 2012, Pipelines (2012) 1084–1091.
[103] M.S. Zarghamee, M. Engindeniz, CFRP renewal of PCCP: an overview, 2014, Pipelines (2014) 932–941.
[104] H. Liang, S. Li, Y. Lu, T. Yang, Reliability analysis of bond behaviour of CFRP–concrete interface under wet–dry cycles, Materials 11 (2018) 741.
[105] P. Marru, V. Latane, C. Puja, K. Vikas, P. Kumar, S. Neogi, Lifetime estimation of glass reinforced epoxy pipes in acidic and alkaline environment using accelerated test methodology, Fibers Polym. 15 (2014) 1935–1940.
[106] B. Li, L. Zhu, X. Fu, Influence of grout strength and residual deformation on performance of rehabilitated RC pipes, J. Pipeline Syst. Eng. Pract. 11 (2020), 04020003.
[107] T. Grafenauer, T. Hayes, J. Vanderwater, M. Kilambi, D. Kasper, Fully structural renewal of 39-inch PCCP water transmission main with swagelining and HDPE, 2015, Pipelines (2015) 1237–1244.
[108] T. Smith, N.A. Hoult, I.D. Moore, Role of grout strength and liners on the performance of slip-lined pipes, J. Pipeline Syst. Eng. Pract. 6 (2015), 04015007.
[109] B. Simpson, I.D. Moore, N.A. Hoult, Experimental investigation of rehabilitated steel culvert performance under static surface loading, J. Geotech. Geoenviron. Eng. 142 (2016), 04015076.
[110] Y. He, X. Fu, B. Li, Test-loading capacity estimation of slip-lined RCPs using a plastic approach, IOP Conf. Ser. Earth Environ. Sci. 474 (2020), 062014.
[111] J. Tetreault, I.D. Moore, N.A. Hoult, Laboratory study on effect of grout choice on culvert rehabilitation using sliplining, J. Pipeline Syst. Eng. Pract. 11 (2020), 04019044.
[112] B. Simpson, N.A. Hoult, I.D. Moore, Rehabilitated reinforced concrete culvert performance under surface loading, Tunn. Undergr. Space Technol. 69 (2017) 52–63.
[113] S.M. Rahmaninezhad, J. Han, M. Al-Naddaf, R.L. Parsons, Behavior of sliplined corrugated steel pipes under parallel-plate loading, J. Mater. Civ. Eng. 31 (2019), 04019242.

[114] R. Chennareddy, Retrofit of Corroded Metal Culverts Using GFRP Slip-Liner, The University of New Mexico, Albuquerque, New Mexico, 2019.

[115] N. Bassett, F. Klingler, S. Lockhart, E. Bantios, J. Edberg, A.G. Mekkaoui, OMID sewer rehabilitation: innovative slip lining of a large diameter sewer without interrupting service, 2017, Pipelines (2017) 225–237.

[116] D. Markert, C. Kratochvil, Val vista water transmission main rehabilitation—steel slip lining of a 90'' PCCP, 2016, Pipelines (2016) 1865–1874.

[117] A. Morris, T. Grafenauer, A. Ambler, City of houston 30-inch water transmission main replaced by compressed fit HDPE pipe lining, 2017, Pipelines (2017) 178–185.

[118] S. Park, K. Hong, Development of lining-board system using light-weight GFRP panels for sewer-pipe construction, J. Kor. Soc. Adv. Compos. Struct. 5 (2014) 23–31.

[119] ASTM F1741-18, Standard Practice for Installation of Machine Spiral Wound Poly (Vinyl Chloride) (PVC) Liner Pipe for Rehabilitation of Existing Sewers and Conduits, ASTM International, West Conshohocken, PA, 2018.

[120] J.D. Goodwin, S. Krautheim, Trenchless trunk sewer rehabilitation without bypass pumping or utility relocation, Pipeline Eng. Construct. (2004) 1–8.

[121] H. Zhu, D. Zhang, T. Wang, H. Wu, V.C. Li, Mechanical and self-healing behavior of low carbon engineered cementitious composites reinforced with PP-fibers, Construct. Build. Mater. 259 (2020), 119805.

[122] D. Zhang, J. Yu, H. Wu, B. Jaworska, B.R. Ellis, V.C. Li, Discontinuous micro-fibers as intrinsic reinforcement for ductile Engineered Cementitious Composites (ECC), Compos. B Eng. 184 (2020) 107741.

[123] K. Yu, L. Li, J. Yu, Y. Wang, J. Ye, Q. Xu, Direct tensile properties of engineered cementitious composites: a review, Construct. Build. Mater. 165 (2018) 346–362.

[124] B. Felekoğlu, K. Tosun-Felekoğlu, M. Keskinateş, E. Gödek, A comparative study on the compatibility of PVA and HTPP fibers with various cementitious matrices under flexural loads, Construct. Build. Mater. 121 (2016) 423–428.

[125] E. Yang, S. Wang, Y. Yang, V.C. Li, Fiber-bridging constitutive law of engineered cementitious composites, J. Adv. Concr. Technol. 6 (2008) 181–193.

[126] M. Sahmaran, M. Lachemi, K.M.A. Hossain, R. Ranade, V.C. Li, Influence of aggregate type and size on ductility and mechanical properties of engineered cementitious composites, ACI Mater. J. 106 (2009) 308–316.

[127] K. Yu, J. Yu, J. Dai, Z. Lu, S.P. Shah, Development of ultra-high performance engineered cementitious composites using polyethylene (PE) fibers, Construct. Build. Mater. 158 (2018) 217–227.

[128] K. Yu, L. Li, J. Yu, J. Xiao, J. Ye, Y. Wang, Feasibility of using ultra-high ductility cementitious composites for concrete structures without steel rebar, Eng. Struct. 170 (2018) 11–20.

[129] K. Yu, Y. Ding, J. Liu, Y. Bai, Energy dissipation characteristics of all-grade polyethylene fiber-reinforced engineered cementitious composites (PE-ECC), Cement Concr. Compos. 106 (2020) 103459.

[130] K. Yu, Y. Ding, Y.X. Zhang, Size effects on tensile properties and compressive strength of engineered cementitious composites, Cement Concr. Compos. 113 (2020) 103691.

[131] H. Wu, D. Zhang, B.R. Ellis, V.C. Li, Development of reactive MgO-based Engineered Cementitious Composite (ECC) through accelerated carbonation curing, Construct. Build. Mater. 191 (2018) 23–31.

[132] R. Ranade, Advanced Cementitious Composite Development for Resilient and Sustainable Infrastructure, Ph.D. Thesis, University of Michigan, Ann Arbor, 2014.

[133] K. Yu, Y. Wang, J. Yu, S. Xu, A strain-hardening cementitious composites with the tensile capacity up to 8%, Construct. Build. Mater. 137 (2017) 410–419.

[134] D.M. Moreno, W. Trono, G. Jen, C. Ostertag, S.L. Billington, Tension stiffening in reinforced high performance fiber reinforced cement-based composites, Cement Concr. Compos. 50 (2014) 36–46.

[135] K. Yu, W. Zhu, Y. Ding, Z. Lu, J. Yu, J. Xiao, Micro-structural and mechanical properties of ultra-high performance engineered cementitious composites (UHP-ECC) incorporation of recycled fine powder (RFP), Cement Concr. Res. 124 (2019) 105813.

[136] V.C. Li, F.P. Bos, K. Yu, W. McGee, T.Y. Ng, S.C. Figueiredo, K. Nefs, V. Mechtcherine, V.N. Nerella, J. Pan, G.P.A.G. van Zijl, P.J. Kruger, On the emergence of 3D printable engineered, strain hardening cementitious composites (ECC/SHCC), Cement Concr. Res. 132 (2020) 106038.

[137] Q. Zhang, V.C. Li, Development of durable spray-applied fire-resistive engineered cementitious composites (SFR-ECC), Cement Concr. Compos. 60 (2015) 10–16.

[138] Y.Y. Kim, H. Kong, V.C. Li, Design of engineered cementitious composite suitable for wet-mixture shotcreting, ACI Mater. J. 100 (2003) 511–518.

[139] V.C. Li, G. Fischer, M. Lepech, Shotcreting with ECC, Spritzbeton-Tagung, Austria, 2009.

[140] G.P. van Zijl, L. de Beer, Sprayed strain-hardening cement-based composite overlay for shear strengthening of unreinforced load-bearing masonry, Adv. Struct. Eng. 22 (2018) 1121–1135.

[141] L. Li, Y. Bai, K. Yu, J. Yu, Z. Lu, Reinforced high-strength engineered cementitious composite (ECC) columns under eccentric compression: experiment and theoretical model, Eng. Struct. 198 (2019) 109541.

[142] S. Xu, B. Zhou, Q. Li, Y. Wu, Mechanical performance of spareable ultra high toughness cementitious composites, J. Hydraul. Eng. 46 (2015) 619–625.

[143] S. Müller, V. Mechtcherine, Use of Strain-Hardening Cement-Based Composites (SHCC) for Retrofitting, International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2018), EDP Sciences, 2018, 09006.

[144] J.S. Davidson, J. Kang, T.C. Grimes, J. Farrell, U.K. Vaidya, B. Pillay, B. Thattaiparthasarat, in: U.D.O.C. Auburn, C.A.H.D. Shelby, E.C. Blastcrete (Eds.), PVA Fiber Reinforced Shotcrete for Rehabilitation and Preventative Maintenance of Aging Culverts, 2009. C.A.E.E. University Of Alabama At Birmingham. Dept. Of Civil.

[145] D.R. Morgan, K. Loevlie, N. Kwong, A. Chan, Centrifugal Sprayed Concrete for Lining Horizontal Pipes and Culverts and Vertical Shafts, 3rd International Conference on Engineering Developments in Shotcrete, 2010, pp. 225–232. New Zealand.

[146] H. Zhu, D. Zhang, Y. Wang, T. Wang, V.C. Li, Development of self-stressing engineered cementitious composites (ECC), Cement Concr. Compos. 118 (2021) 103936.

[147] ASTM C497M-20a, Standard Test Methods for Concrete Pipe, Concrete Box Sections, Manhole Sections, or Tile (Metric), ASTM International, West Conshohocken, PA, 2020.

[148] F. Wittmann, G. Van Zijl, Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC), Springer, 2011.

[149] V.C. Li, Engineered cementitious composites (ECC) material, structural, and durability performance, in: E. Nawy (Ed.), Concrete Construction Engineering Handbook, CRC Press, 2008 (Chapter 24).

[150] M. Sahmaran, V.C. Li, De-icing salt scaling resistance of mechanically loaded engineered cementitious composites, Cement Concr. Res. 37 (2007) 1035–1046.

[151] H. Wu, D. Zhang, Y. Du, V.C. Li, Durability of engineered cementitious composite exposed to acid mine drainage, Cement Concr. Compos. 108 (2020) 103550.

[152] M. Ohno, V.C. Li, Sulfuric acid resistance of strain hardening fiber reinforced geopolymer composite, Indian Concr. J. (Dec, 2019) 47–53. https://www.icjonline.com/archives/2019/12 http://acemrl.engin.umich.edu/wp-content/uploads/sites/412/2019/12/SULFURIC-ACID-RESISTANCE-OF-STRAIN-HARDENING-FIBER-REINFORCED-GEOPOLYMER-COMPOSITE.pdf.

[153] M.D. Lepech, V.C. Li, Water permeability of engineered cementitious composites, Cement Concr. Compos. 31 (2009) 744–753.

[154] V.C. Li, E. Herbert, Robust self-healing concrete for sustainable infrastructure, J. Adv. Concr. Technol. 10 (2012) 207–218.

[155] V.C. Li, E. Yang, Self Healing in Concrete Materials, Self Healing Materials, Springer, 2007, pp. 161–193.

[156] M.D. Lepech, V.C. Li, R.E. Robertson, G.A. Keoleian, Design of green engineered cementitious composites for improved sustainability, ACI Mater. J. 105 (2008) 567.

[157] G.A. Keoleian, A. Kendall, J.E. Dettling, V.M. Smith, R.F. Chandler, M.D. Lepech, V.C. Li, Life cycle modeling of concrete bridge design: comparison of engineered cementitious composite link slabs and conventional steel expansion joints, J. Infrastruct. Syst. 11 (2005) 51–60.

[158] N. Mohammad, Trenchless Technology Piping: Installation and Inspection, McGraw-Hill Professional, US, 2010.

[159] C. Paglia, F. Wombacher, H. Böhni, The influence of alkali-free and alkaline shotcrete accelerators within cement systems: influence of the temperature on the sulfate attack mechanisms and damage, Cement Concr. Res. 33 (2003), 387–39.

[160] L. Roberto Prudhcio Jr., Accelerating admixtures for shotcrete, Cement Concr. Compos. 20 (1998) 213–219.

[161] Y. Lin, D. Lawley, L. Wotherspoon, J.M. Ingham, Out-of-plane testing of unreinforced masonry walls strengthened using ECC shotcrete, Structure 7 (2016) 33–42.