Cementation in adhesive dentistry: the weakest link
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CHAPTER 1

Introduction
Introduction

An important goal of dentistry is the prevention of disease and hereby the preservation of tooth tissue. However, even though most individuals develop a beautiful set of teeth during childhood and early adolescence, natural tooth tissue can be lost in several ways. An important and widely spread pathological process of mineral tissue loss is dental caries. It affects the major part of the world population [1]. Bacteria in the oral cavity metabolize dietary sugars into lactic acid, which dissolves human enamel. As a consequence, natural tooth tissue is lost [2]. Other causes for tooth tissue loss may be trauma [3] or different types of wear, such as abrasion, erosion, attrition and abfraction [4-6]. The loss of tooth substance not only limits function [7], it also weakens the tooth, making it less resistant to fracture [8]. Apart from causing functional problems, deterioration of the human dentition during life has negative psychosocial effects. It is among others associated with loss of self-confidence, aging, and loss of attractiveness [9, 10].

In dentistry we are familiar with a long-lasting search for optimal treatment of caries lesions and materials for restoration of defects. Until a few decades ago, this usually resulted in amalgam restorations or cast metal restorations, for which a lot of natural tooth tissue has to be sacrificed, to meet the preparation criteria of the restorations. The preparation guidelines were dictated by the need for macromechanical retention and optimal strength of the restoration. The dental cements of these days, e.g. zinc-oxide eugenol cement, simply added friction i.e. macromechanical retention instead of micromechanical or chemical retention. Invasive preparations were made in order to provide sufficient retention to the restoration. The restorations were designed to last as long as possible, focusing on the survival of the restoration rather than the survival of the tooth. Since the acknowledgement of the “repeat restorative cycle” [11], the focus has shifted towards minimally invasive dentistry. This results in a conservative approach towards restorative dentistry, and when restoration cannot be avoided, in the objective to cause as little as possible damage to tooth tissue, and the patient as a whole [12]. Minimally invasive dentistry has largely been made possible by the introduction of adhesive dentistry. Adhesion of resins to enamel has been possible since the acid-etching technique was first described in 1955 [13]. An important advantage of adhesive materials is the diminished need for mechanical retention by preparation form, with less additional iatrogenic damage to
healthy tooth tissues [14]. The resin composite restorative materials have evolved into versatile materials for different indications with good esthetic and mechanical properties, and high bond strengths to both enamel and dentin [15]. Nowadays, these are the materials of first choice for replacement of natural tooth tissue [15, 16].

Even though the focus of the dental field has shifted more towards preventive and minimally invasive dentistry, the clinician is still often confronted with substantial loss of tooth substance. When restoring the function of such a tooth, the preservation of natural tooth tissue while using biocompatible materials is an important goal. The so-called “dynamic treatment concept” states that the simplest treatment option, which keeps as many as possible treatment options open, is beneficial to the tooth, because hereby the survival time of the tooth is prolonged. The objectives of the dynamic restorative concept can be achieved by using adhesive bonding systems, resin composites, and fiber-reinforced composites, which will all be discussed in detail below.

Adhesive dentistry is based on the bonding of various substrates. This can be the bond between a restorative material and dentin or enamel, the bond between cement and tooth tissue, etc. Even though the presence of these bonds have revolutionized dentistry, they form the weakest link of the entire adhesively placed restoration. In the sections below each facet will be described of restoring a tooth with a post-and-core direct restoration and a covering composite direct or indirect restoration. In this thesis the focus has been put on the bond between resin cements and tooth tissue, and the bond between resin cements, fiber-reinforced composite posts, and the composite material.

**Posts**

When the pulp of a tooth is exposed to oral bacteria, either by a trauma, an iatrogenic process, or due to (indirect) contact with the oral cavity through a carious lesion, this can result in irreversible pulpitis [17], pulp necrosis [18] and periapical periodontitis [19, 20]. This makes endodontic treatment necessary [19, 20], which further reduces the amount of natural tooth tissue, and thereby the resistance of the tooth [8, 21-23]. Sometimes, the remaining tooth is destructed in such a way that it cannot be built up with a regular direct restoration. In these cases, a post can be placed inside the root
canal to provide additional retention for the rest of the core build-up [23-25]. It must be stressed that posts do not reinforce roots [21, 25]. Actually, the center of the root is a neutral area regarding stress concentration, therefore there is not even a need for reinforcement in the area [26].

In the twentieth century, it was common practice to build up an endodontically treated tooth with a cast post-and-core restoration [23, 24, 27]. This is a treatment option which has a lot of clinical evidence speaking for it [23, 28]. However, the main disadvantage is that vertical root fracture is a common mode of failure with these restorations [21, 29]. This virtually reduces the further treatment options to extraction of the tooth [21, 30-32]. The clinical procedure for the cast post-and-core restoration requires an extra appointment. Therefore, a temporary restoration has to be made, which has an inferior coronal sealing, possibly leading to re-infection of the root canals [23]. Microleakage can be minimized by placing the post directly after preparing the post space, as is possible with a prefabricated post [26]. In the last decades, numerous types of prefabricated root canal posts have been used, including metallic, carbon fiber, and zirconia posts, in various shapes, sizes, and surface designs [23, 26, 33]. Metallic posts can be considered less ideal from an esthetic point of view, while zirconia posts are brittle in nature. Adhesive bonding to the cement remains a problem with zirconia, and retrieval of zirconia posts is difficult, if not impossible [23, 24]. The high elastic modulus of both metallic and zirconia posts can cause high stresses to be transferred to the root dentin, possibly resulting in root fractures [21, 34].

Nowadays, there is a trend towards the use of prefabricated tooth-colored fiber-reinforced composite (FRC) posts, which are cemented in the root canal using a resin cement while the core is built up with a resin composite [23, 32, 35]. Tooth-colored FRC posts are made of quartz or glass fibers, embedded in a matrix of epoxy or methacrylate resin. The fibers are oriented parallel to the long axis of the post. The fibers are silanized prior to embedding them in the resin matrix, to ensure a stable bond between the fibers and the resin matrix [24, 36]. Although more randomized clinical trials are needed to establish the evidence of fiber-reinforced composite post restorations at a sufficient level [37], the scientific base is getting stronger [38]. The clinical success and survival rates reported so far for these restorations are very high [24, 29, 38]. This adhesive treatment option is beneficial in terms of retaining sound tooth tissue as much as possible. Undercuts do not have to be removed, and the latest double-tapered anatomical shapes of the posts require less adjustment to the natural
anatomy of the root canal in order to be placed [24]. Successful bonding minimizes the “wedging effect”, which can cause root fracture, and is often observed with tapered metal posts which are non-adhesively bonded. Metal-free posts do not pose the risk of allergic sensitization or corrosion, and if needed can be removed fairly easy [25].

Debonding is the most common mode of failure of post restorations [24, 29, 38]. Another common failure mode is endodontic failure [29], which may be a result of microleakage due to partial debonding of the post-and-core restoration. Debonding, however, is a non-catastrophic failure mode, which leaves the tooth in the mouth to undergo further treatment [24, 38]. It facilitates one of the most important treatment goals in dentistry, which is to remain the teeth in function for as long as possible. Vertical root fracture is uncommon with these restorations [29, 38]. This has been attributed to the elastic modulus of the fiber-reinforced composite material, which is closer to natural dentin than the metal alloys used in cast restorations, or for instance ceramic materials [24, 34, 39, 40], while maintaining a high flexural strength [39]. However, the placement of a (fiber) post still poses some risks. In most cases the root canal has to be prepared prior to placement of a post, which further weakens the tooth [8, 21, 22]. There is also a low risk of perforation of the root walls during preparation, diminishing the prognosis of the tooth [23].

It is important to realize how much extra retention the post can add to the restoration, and if this is worth the removal of additional sound tooth tissue, no matter how small this amount might be. If a sufficient amount of tooth tissue is still present to provide retention to a direct build-up, the extra retention provided by the post is not beneficial to the survival of the restoration as a whole, as shown in a long-term clinical study [41]. Therefore, posts should only be used when other means of core retention are lacking [8, 22, 23, 42]. The fracture resistance of a tooth is highly dependent on the amount of residual tooth tissue [22]. Careful interpretation of the high success rates obtained in vivo is important, as in some in vivo studies posts were placed while retention of a core build-up was still possible without the use of a post [41, 43]. Moreover, other factors, apart from the amount of residual tooth tissue, such as ferrule, and magnitude and direction of the load probably have greater influence on clinical performance than the type of post used [26].
Adhesive challenges

The retention of restorative materials, for instance fiber posts, depends on the quality of the bond at different interfaces. Not only the interface between the cement and the tooth tissue is important, the bond between the cement and the restorative surfaces also plays an important role [35]. The difficulty of reliable cementation is demonstrated by the fact that debonding of fiber posts is the most common failure mode for these restorations [29, 38], as previously stated. Moreover, it has been shown that different interfaces of post-and-core restorations are imperfect from a quality standpoint [32]. This is illustrated by the observation that the dislocation resistance of bonded fiber posts is largely due to sliding friction [44].

A stable adhesion between cement and tooth tissue, being either dentin or enamel, is a great challenge, due to the negative influence of a variety of intervening factors [24]. For instance, the contamination of dentin with a desensitizing agent may reduce retention, at least with some luting cements [45]. Furthermore, eugenol has been shown to inhibit resin polymerization. In practice, all traces of eugenol-containing temporary cement have to be removed thoroughly for maximum adhesion of the resin cement, because they can reduce the tensile bond strength of resin cements. Conventional and resin-modified glass-ionomer cements do not seem to be affected by eugenol [45, 46]. Also, calcium hydroxide and potassium oxalate may reduce adhesion when used in combination with for instance glass-ionomer or resin cements [45]. In general, after endodontic treatment, a thick “secondary” smear layer is present on the canal walls, consisting pieces of plasticized gutta-percha and (eugenol-containing) sealer [24]. Moreover, sodium hypochlorite and other endodontic irrigants may significantly affect dentin quality [47]. It is therefore important to clean the canal walls very carefully prior to post cementation [24]. It can be stated that any contamination of dentin may lead to a decrease in bond strength. Moreover, it has been reported that radicular dentin offers less favorable bonding conditions compared to coronal dentin [35], which makes the bonding of fiber posts even more challenging.

The most frequent site of adhesive failure of a post restoration is at the resin cement-dentin interface [35], which makes this interface the main point of interest. However, the post-cement bond also needs to be considered. In the case of fiber posts, different surface pretreatment methods have been tested to improve chemical and/or micromechanical retention, for instance silanization, acid etching, sandblasting and
silica coating [35]. The positive effects of silanization are questionable, while acid-etching with hydrofluoric acid produces substantial damage to the glass-fibers and affects the integrity of the post and cannot be recommended. The main problem with sandblasting is that both the matrix and the fibers of the post are affected, which can also lead to structural damage of the post [35]. More research is needed to establish the effectiveness of different pretreatment methods. Bonding of resin cements to zirconium oxide materials still poses a problem [48]. Acid etching and silanization do not improve the bond strength, since little or no silica is present in this material on which to base a chemically stable bond. Therefore, the bond is only micromechanical in nature [36].

Cements

The ideal cement has to meet many requirements. Not only should it provide a durable bond between the restoration and the tooth, be able to wet the tooth and restoration surface, exhibit adequate film thickness and viscosity [46], it also has to be biocompatible, have good mechanical and esthetic properties, be easy to handle, have low solubility, have anti-caries activity, have adequate radiopacity, and preferably be cost-effective [45]. A dentist can choose from a wide array of cements when cementing a post or an indirect restoration. Each cement has its own characteristics, advantages and disadvantages. The selection of an adequate cementation mode is affected by both the characteristics of the restoration, the clinical covariables, and the properties of the used material [49].

When choosing an appropriate adhesive system, the clinician can be overwhelmed by the different options available on the market. With full metal and metal-porcelain restorations, zinc-phosphate and glass-ionomer cements are widely used. Nowadays, with composite and ceramic based restorations being the most popular, the three cement types that are most used are glass-ionomer cements, resin cements and a combination of both: resin-modified glass-ionomer cements. These cements will be discussed in more detail below.
Glass-ionomer luting cements

The setting of glass-ionomer cements (GIC’s) is based on a chemical reaction in which polyalkenoate acid dissolves the outer surface of the glass fillers releasing aluminum, calcium, and fluoride ions. The aluminum and calcium ions form crosslinks between the polyalkenoate chains, resulting in a set material [50]. The adhesion to tooth tissue is thought to be based on the formation of ionic bonds at the tooth-cement interface as a result of chelation of the carboxyl groups in the acid matrix with the calcium and phosphate ions in the tooth tissue [46, 51]. A popular feature of glass-ionomer cements is their fluoride-release as it is presumed that this will lead to a reduction in caries activity [45, 52]. However, the evidence for actual caries reduction remains inconclusive [45, 53]. Although fluoride is released, the quantity of cement at the margin may be too small for any significant cariostatic effect to be observed [46]. Advantages are good flow properties, chemical adhesion to tooth tissue and base metals, good translucency, adequate strength, and relatively low cost [54]. A disadvantage of GIC’s is their sensitivity to early moisture [45]. Moreover, it takes several months for the reaction to complete [54], the working time is quite short [54], and the radiolucency of GIC’s is usually quite low compared to resin cements [45]. GIC’s are recommended for the cementation of cast metal restorations, e.g. inlays, onlays, crowns, and bridges, as well as for metal-ceramic and high-strength all ceramic crowns and bridges with a macroretentive preparation design and adequate marginal fit. Due to the low adhesive properties of the materials, however, conventional GIC’s are contraindicated for the cementation of conventional glass-ceramic restorations and for all types of ceramic inlay restorations [49]. They are also contraindicated for the cementation of (fiber) posts, since the vibrations due to the subsequent preparation of the core could negatively affect the cement layer [54].

Conventional resin cements

Resin cements are chemically comparable to resin composite filling materials, but they are less viscous to facilitate their use in thin layers [15, 54]. They can be bonded to restorative materials and tooth tissue in different ways, through the use of an adhesive system. There are many types of adhesive systems available, from classical three-step etch-and-rinse to one-step systems [54, 55]. Bonding to enamel occurs through the penetration of resin between the hydroxyapatite crystals and rods of etched enamel, as described by Buonocore [13]. Bonding to dentin is more complex in nature, and
comprises penetration of hydrophilic monomers in the collagen layer that remains after acid-etching of the dentin, which results in the formation of a “hybrid layer” or “resin-dentin interdiffusion zone” [46]. The adhesive systems used today differ in their interaction with the smear layer. Adhesive systems that use a separate conditioner, usually comprising of application of an etching gel of 35-37% phosphoric acid, which is washed away with water, are designed to dissolve the smear layer which is present after preparation of the tooth substrate. Alternatively, self-etching adhesives use a mild self-etching primer, which is air dried, and results in modification of the smear layer, incorporating it in the adhesive layer. In both cases the acid-conditioning is followed by priming and bonding of the substrate, which may or may not be separate steps. The current classification of adhesives is based on the working mechanism and the number of steps needed [14, 56].

Self-adhesive resin cements
Recently, self-adhesive cements were introduced [57]. These are defined as cements based on filled polymers designed to adhere to tooth material without any pretreatment. Since these cements do not require a separate adhesive system, clinical acceptance and efficiency may be enhanced. These products, although marketed as resin cements, really are hybrid materials that combine features of self-etching adhesives and resin composites. They are similar to compomer materials, but with a different acidic monomer concentration. Acid-functionalized methacrylate or related monomers are incorporated in these cements, for direct bonding to tooth tissue, through a polyacid matrix structure. This is either based on a preformed polyalkenoate or one that is created in situ during a curing process involving acidic monomers [57]. The polymerization reaction is based on the cross-linking of monomers with phosphoric acidic functional groups, which bind to calcium in the hydroxylapatite to form an attachment between the methacrylate network and the tooth. Ions released from the acid-soluble filler neutralize the remaining acidic groups to create a chelate reinforced three-dimensional methacrylate network. Even though hardly any resin tags are formed, there seems to be a good chemical interaction with calcium from hydroxyapatite [57]. They show a relatively strong bond to dentin, even in the absence of a hybrid layer, but the bond strengths than can be obtained with resin cements with a separate adhesive system are still higher [57]. The bond strength values seem to be in between what can be achieved with a resin with separate adhesive system and a glass-
ionomer cement, which is in line with the expected values based on its chemical formulation [57]. The bond strength to enamel is more challenging with these materials and needs further attention. The first product marketed in this material group was RelyX Unicem (3M ESPE, Seefeld, Germany), a material studied in most chapters of this thesis. Although long-term results are not yet available, this material seems to have a clinical performance comparable to established resin cements [57].

Advantages of resin cements in general, apart from their ability for adhesive cementation, are their excellent physical properties [54, 57]. They generally exhibit high flexural strength, diametral tensile strength, modulus of elasticity, fracture toughness, and hardness compared to water-based cements [45]. Moreover, they show high compressive strength values, high resistance to fatigue, and are virtually insoluble in the oral environment. They also show an improved marginal wear resistance in comparison to (resin-modified) glass-ionomer cements [46]. The ability for adhesive cementation of restorations are great advantages of resin cements [54, 57], especially since the preparation for an indirect restoration will not always provide macromechanical retention. Resin composites are not only able to bond to tooth tissue, they also bond to resin composite restorative materials, and to pretreated porcelain and base metals. The bonding to silanized and/or hydrofluoric acid-etched porcelain results in an increased fracture resistance of ceramic materials when cemented to tooth tissue [46]. Self-adhesive cements seem to achieve high bond strengths to restorative materials like zirconium oxide and metals as well [57]. Another advantage of resin cements is their higher radiopacity compared to glass-ionomer cements [45].

A disadvantage of conventional i.e. non self-adhesive resin cements is their high technique-sensitivity, including the need for well-controlled clinical circumstances regarding isolation [45, 46, 57], since most adhesive systems are adversely affected by high humidity [45]. Their technique-sensitivity is illustrated in studies reporting significant differences in bond strength between operators performing the same bonding procedure [26]. This may widen the gap between their performance under ideal conditions in the lab and in everyday practice. Even though the combination of etch-and-rinse adhesives and dual-cured cements for the cementation of fiber posts is currently considered the best option, it should be pointed out that the success of the final restoration depends on the accuracy of each separate step. More technique-sensitive materials may therefore be less reliable. The difficult
access to the post space *i.e.* the root canal is another problem, which makes clinical control over each of the treatment steps, *e.g.* rinsing and drying, more difficult [24]. Over-etching of dentin for instance, causes an impaired resin impregnation which increases nanoleakage, but can also cause structural damage to the dentin matrix, and especially the collagen fibrils [14].

In general, other disadvantages of resin cements are the difficult removal of excess material, and their high relative cost [54]. Self-adhesive resin cements are probably, due to their formulation, less resistant to abrasion, erosion, and fracture compared to conventional resin cements [57]. Compared to conventional resin cements, they show an increased microleakage, comparable to the microleakage found for resin-modified glass ionomer cements. In vitro microleakage tests seem hardly dependent on the marginal adaptation of the cast restoration, probably because the weakest link is at the adhesive interface [45]. Resin-cements are also susceptible to water sorption. This will adversely affect the mechanical properties of the material. On the other hand, it is often reported to be beneficial because it counteracts the polymerization shrinkage [45]. Water sorption is a long-term effect, however, and it cannot prevent the damage to the bonded interface that is inflicted by the shrinkage stress initially.

Resin cements are recommended clinically for the cementation of fiber-reinforced composite posts, resin-bonded bridges, ceramic restorations, [15, 54], and ceramic veneer restorations [49]. The main indication for adhesive cementation of oxide ceramics is to avoid loss of retention [49], especially when the preparation lacks optimal retention and resistance form [46]. Resin cements may be a solution in these cases, as resin bonding is often reported to provide better retention for indirect restorations than conventional cements [45]. Allergies to resin cements have been reported, but are quite rare [45]. The risk of adverse reactions is thought to be higher for dentists than for patients [58]. The biocompatibility of resin cements is related to its degree of conversion, and complaints of sensitivity may be due to incomplete polymerization [45]. The degree of cure seems to be an important variable with dual-cured specimens showing less cytotoxicity compared to self-cured specimens [59].
Resin-modified glass-ionomer cements

Resin-modified glass-ionomer cements (RMGIC’s) are hybrid materials. Essentially, they are glass-ionomer cements to which water-soluble polymers or polymerizable resins are added [54].

They were designed to overcome two major problems with conventional GIC’s, being low early strength and high solubility [54]. RMGIC’s are indeed less vulnerable to early moisture compared to classical glass-ionomer cements [45, 46], and because the resin portion can be light-cured, this gives a higher early strength, while the acid-base reaction of the glass-ionomer portion is still taking place [54]. The hybrid material has better mechanical and physical properties compared to conventional glass-ionomers, though lower than resin cements, while the material still retains the same possibility for fluoride release compared to conventional GIC’s [46, 54]. Although they are less soluble compared to conventional GIC’s [46], they can, however, suffer from hygroscopic expansion, and are therefore not recommended for cementing all-ceramic restorations and (fiber) posts because of the risk of expansion-induced restoration or root fracture [46, 54].

They are primarily indicated for the cementation of metal and metal-ceramic indirect restorations, as well as high-strength alumina or zirconium core all-ceramic crowns [54]. The manipulation is similar to conventional GIC’s, with easy mixing and the lack of need for multiple bonding steps [46, 54]. The film thickness is also adequately low [46].

Comparable to the resin cements, the monomers in RMGIC’s may induce allergic reactions [46]. This applies especially in cases where the material is placed in bulk, and the resin component is supposed to be light-cured. Even though the acid-base reaction can take place at any depth, if the light cannot reach deeper layers of the material, the resin polymerization will not (fully) take place, which means that free (HEMA) monomers are present in the material [50].

In this thesis, the tested cements fall into the categories of resin-modified glass-ionomer cements, resin cements and self-adhesive resin cements.
Curing of composites

When a resin cement sets, a polymerization reaction takes place, which results in cross-linking of the monomers of the organic matrix. This results in volumetric shrinkage of the cement. The amount of volumetric shrinkage is dependent on the composition and degree of conversion of the organic matrix, and the filler volume [60]. The volumetric shrinkage of resin composite restoratives is usually around 2-3% [60, 61]. For most flowable composites and dental resin cements however, due to their lower viscosity achieved through higher resin content, the volumetric shrinkage lies around 4-5% [60-62].

In the past, dentists had to make a choice between a chemical curing or a light-curing cement. Chemical curing, also known as self-curing, starts with mixing two components, often a powder and a liquid, or two gels. Light-curing is started when the cement is irradiated with blue light in the visible spectrum with a wavelength of 400 to 500 nm [63]. The light-cured cement has the advantage of being easy to handle and the curing can be carried out at a convenient time. Chemically curing cements have the disadvantage that the curing starts as soon as two components are mixed together, which limits the working time of the cement. On the other hand, it takes quite a long time to achieve a degree of cure that permits early loading of the restoration [62]. Dual-cure cements can be, as the name suggests, cured both chemically by the joining of two components, and/or by adding light to this mixture. Dual-cured cements have the advantage that the material cures in locations inaccessible for the light, for instance in deeper parts of a post space, or beneath restorative materials, such as indirect restorations. However, it should be noted that for many dual-cured cements the degree of cure obtained after solely self-curing is not as high as with dual-curing [62, 64, 65]. This lower degree of cure also results in lower mechanical properties [66-68]. Apart from that, the lower degree of cure may also increase the risk of pulpal toxicity due to the elution of residual monomers [62].
C-factor and contraction stress

When making a direct restoration, or cementing an indirect restoration or prefabricated fiber post, the shrinkage of the direct resin composite or the resin cement is counteracted by adhesion to the cavity walls [60], and in the case of cementing indirect restorations and posts also by the adhesion to the restoration surfaces. The level of confinement is expressed by the Configuration Factor or C-factor, which was described by Feilzer et al. as the ratio of bonded to unbonded (free) surfaces of a restoration [69]. This mathematical value makes it possible to correlate confinement conditions with stress values [60]. The higher the C-factor gets, the higher the contraction stress of the restoration becomes. It has been shown that contraction stress causes flow of the outer free surfaces of a restoration, which compensates for the polymerization shrinkage and partially relieves contraction stress [70, 71]. Mixing porosities act as free surface and therefore increase the ability for the material to flow, causing a lower polymerization contraction stress in the material [72]. However, due to oxygen inhibition, this also results in a lower degree of cure. In restorations with low C-factors the ability for stress relief by flow is higher than in restorations with high C-factor, which results in a higher contraction stress in high C-factor geometries. If the polymerization stresses are greater than the adhesive or cohesive strength of the cement, failure will occur [45]. A direct relationship has been demonstrated between polymerization shrinkage and marginal integrity, both in Class V restorations [60, 73] and in the margins of bonded porcelain inlays [60, 74]. Therefore, the higher the C-factor, the likelier debonding becomes [69].

When placing direct fillings, the C-factor typically ranges from $C = 0.5$ to $C = 5.0$ [69]. However, when cementing restorations, being either indirect restorations or prefabricated fiber posts, the C-factor reaches extremely high values, which are estimated to be in the range of 200 in the case of post cementation [75]. It has indeed been shown that the high C-factor within the post space has a detrimental effect on the bond strength when cementing posts with resin cement [75]. In clinical practice however, the cavity configurations are often very complex, which leads to a heterogeneous stress distribution throughout the restoration, which makes interpretation more difficult [60].

In clinical practice, much effort has been put into diminishing the effects of high contraction stress. In direct restorations, the clinician has the possibility to use the
incremental technique to diminish the consequences of contraction stress. This incremental technique, although not fully supported scientifically, consists of the idea of inserting the composite in small increments instead of in bulk. Apart from lowering the C-factor, the smaller increments exhibit smaller absolute values of shrinkage stress. It also allows better curing of the separate layers. Another method of lowering the shrinkage stress is the application of a low stiffness material between the composite restoration and the cavity walls, which not only increases the compliance of the bonding substrate, but also leads to a more uniform stress distribution [60]. Unfortunately, both methods are not suitable for use in cementation procedures, which highly limits the possibility for stress relief in cement layers. Moreover, compliance of the cavity walls is not likely in the case of cemented posts or indirect restorations.

Contraction stresses in resin cements are also reduced if chemical curing is used instead of light-curing [45, 76]. When a composite is light-cured, a very fast polymerization reaction takes place. In these cases, virtually no chance for stress relief by viscous flow remains, because the polymer matrix becomes quite rigid in a short time. From this point on, the stress starts to build up. On the other hand, self-cured composites, because of their slower reaction rate, and also because they generally exhibit a lower degree of conversion, develop lower contraction stress values [60]. Several “soft-start” curing regimes have been tested to overcome the problem of rapid polymerization resulting in stress development in light-cured composites. However, the stage in the conversion where the composite becomes too rigid for viscous flow is reached at a relatively low degree of conversion, which limits the benefits of these regimes, because significant reductions in contraction stress are often not obtained. Moreover, this method can lead to lower degree of conversion [60]. Since clinically a high degree of conversion leads to a higher elastic modulus and better clinical performance, maximizing viscous flow seems to be key to reduce stress [60].

Besides the high C-factor, the wall-to-wall contraction also plays a role in cementation. Especially in thin layers, the wall-to-wall contraction may be much higher than expected theoretically, since the contraction parallel to the walls becomes so strongly restrained that it will be forced in the axial direction (meaning that the volumetric shrinkage which normally takes place in three directions is forced to take place in one direction, and therefore the wall-to-wall contraction comes very near to the volumetric contraction of the material), especially if the opposing walls do not yield to the polymerization stresses [77], as is the case with the cementation of a fiber
post, or an indirect restoration. This phenomenon can be explained by the near absence of flow capacity in these thin layers [77].

The volume of the shrinking composite is a factor to consider as well. If two specimens with the same C-factor would differ in volume, the specimen with the highest volume would show the highest contraction stress. This means that the C-factor is only applicable when comparing restorations with similar volume [60].

**Indirect restorations**

Sometimes a direct restoration, with or without extra retention of the post build-up, is not expected to provide enough resistance to tooth fracture. Especially when the marginal ridges are lost [25], which in combination with endodontic access preparation results in maximum tooth fragility [47], cuspal coverage is a significant variable for long-term success of endodontically treated posterior teeth [8]. In these cases, an indirect restoration is often made. Moreover, teeth are often provided with indirect restorations as part of fixed partial dentures for the replacement of missing teeth.

Indirect restorations can be manufactured from a large variety of materials [78]. Metal alloys such as gold and palladium alloys are widely used to replace and restore missing tooth tissue [78, 79]. Through the years, with patients requesting more esthetically pleasing restorations, porcelain fused to metal restorations became very popular [48]. They had some esthetical disadvantages though, like a suboptimal translucency, and a visible line of metal at the cervical margin of the restoration [48]. Ceramic restorations can solve those esthetical problems, and match the natural tooth very well. However, they have the disadvantage of being very prone to fracture. Better results have been obtained by using substructures of aluminum oxide [48] and later zirconium oxide, which gives the restorations a very strong base, on which more beautiful ceramic materials can be pressed or fired [48, 80]. Alternatively, resin composites can be used as indirect materials creating restorations with good esthetic properties [79, 81]. However, composite materials have totally different material properties compared to ceramic materials, which can lead to a different stress distribution in the tooth-restoration complex [82]. Although there is a large variety of indirect restorations concerning shape, material and properties, they have in common that they all have to be luted to the tooth. Since the adhesion of the restoration is
dependent on the cement layer between the tooth and the restoration, this cement layer, and the cementation procedure, is an important factor in the longevity of the restoration [46, 49, 78].

By placing a full crown, it is possible to incorporate a ferrule, which is described as an encircling band of cast metal around the coronal surface of a tooth [83]. This is an important aid to increase the fracture resistance of a tooth [26]. It has been shown that crown placement is positively related with the survival of endodontically treated teeth [84]. Moreover, when a crown with sufficient ferrule is placed, the post becomes less important [47], which illustrates the importance of ferrule.

**Challenges for the adhesive bond**

After the restorations have been (successfully) cemented, they have to be able to withstand repeated exposure to physical and chemical stressors. This is a difficult environment in which to maintain an hermetically sealed system [14, 23]. Even though adhesive systems produce a good dentin bond strength immediately after bonding, interfacial aging due to degradation of the hybrid layer is a major concern [14]. This is illustrated by the fact that debonding and persistent or recurrent peri-apical infections are common causes of failure for post-and-core restorations [29, 38] while recurrent caries, loss of vitality, debonding and marginal discoloration are known complications with cemented indirect restorations [85-87], which may also be the result of lacking marginal integrity.

Even in the healthiest person, the oral environment is rich in microorganisms [23]. Moreover, our oral cavities are aqueous environments, in which the cements are not only susceptible to water sorption or dissolution, but also to enzymes from saliva and dentin [88, 89]. Water not only leads to water sorption, which causes a significant decrease in the modulus of elasticity of a resin, it also causes resin hydrolysis, and disorganization and degradation of collagen fibrils in the dentin, thereby weakening the resin-dentin bond [14]. Even in the absence of bacterial enzymes, proteolytic enzymes from the dentin itself may degrade collagen matrices and therefore the bond to dentin [14].
Apart from chemical factors present in the oral environment, the restoration has to withstand physical forces as well [14]. The cement layer does not only have to provide sufficient retention to the restoration, it will also have to withstand stresses due to chewing, biting and perhaps even parafunctional activities [14]. These stresses are partially transferred from the restoration to the tooth and core build-up adhesively bonded to the remaining tooth tissue, and partially to the cement layer with which the restoration is cemented. The balance of these stresses is highly dependent on the material used for the direct and indirect restoration, and the amount of residual tooth structure. The less residual dentin there is, and the lower the e-modulus of the materials used will be, the more stress will be exerted on the remaining tooth structures through the cement layer, with possibly detrimental consequences [26, 82]. Higher occlusal forces, like in the case of parafunctional activities, were associated with higher failure rates of post-restored teeth clinically [21].

Testing methodology

There are different ways to predict the clinical performance of dental restorative materials. In terms of methodology, the ideal test set-up is a randomized controlled clinical trial (RCT), in which the experimental group and one or more control groups are tested double-blind and subjects are randomly assigned to different groups. This is the gold standard for clinical study. Since this approach is often difficult to carry out due to practical limitations, variations are executed. However, the further the study design deviates from the RCT, the less valid the results will be.

Cemented restorations are complex systems with a great variety of factors influencing the result [26]. To be able to test one or a few of these variables separately, in vitro tests can be used. In vitro-tests can be designed to focus on a few variables influencing each other. Tensile, diametral tensile, and flexural strength values can be obtained in vitro, as well as bond strength values, e-modulus, shrinkage, shrinkage stress, etcetera. Flexural strength of a material for instance, can be tested using a three-point or four-point bending test, while bond strength can be tested using (micro)tensile tests, (micro)shear bond strength tests, or (micro)push-out tests, and variations on these tests. Each test has its advantages and disadvantages, and it is known that using different test methods may lead to varying test results [90]. The bond strength values
obtained in the different tests are influenced by the specimen geometry, loading condition, film thickness and modulus of elasticity of the materials involved. Therefore, differences in bond strength value reported in literature are not only the result of one material really performing better than other materials, but also the result of using different testing methodologies. This is mostly due to the different forces present in these systems, in combination with the brittle nature of most dental cements and composite materials [90]. Flaws like voids or air bubbles in the adhesive interface can act as a point of initiation for failure of the specimen, and it is therefore accepted that using smaller samples, as used in microtensile and microshear tests often leads to higher bond strength values than using larger samples, because the presence of flaws is more likely in the latter [90, 91].

Currently, Finite Element Analysis (FEA) is often used to calculate forces present in restorative systems. The principle of FEA has been used to calculate strength in structures for many years, and has now gained a position in dentistry as well. The principle is based on manufacturing a computer model, either two- or three-dimensional, of the specimen being studied. This model consists of “elements”, which are essentially building blocks of the model. These elements are connected at the corners (“nodes”) to form a mesh. Material properties (e-modulus, Poisson’s ratio) can be assigned to the different elements, and stresses can be applied from a certain direction. Also, specific boundaries can be set, for instance the (dis)ability to move in a certain direction. This way, stresses for each element can be calculated, and through this data, stress distributions within the model as a whole. Since within the models internal stresses can be calculated, which is of course not possible with other in vitro tests, it might provide valuable information regarding failure mechanisms of restorations [92].
Aim and outline of the thesis

The aim of this thesis is to gain a better understanding of the dynamics involved in cementing a direct or indirect restoration to natural tooth tissue, especially root dentin, and to explore ways to cement these restorations more effectively and reliably. This thesis mainly focuses on the influence of C-factor, mode of polymerization, shrinkage stress and strain and pretreatment of fiber posts on the cohesive strength of the cement itself as well as the bond strength to dentin and fiber post material soon after cementation of posts and indirect restorations. Furthermore, the clinical success and survival of resin composite indirect restorations cemented with two different cements are evaluated.

The first specific aim of this thesis is to investigate the influence of polymerization mode and C-factor on cohesive strength of five different dual-cured resin cements in vitro. The cements will either be self- or dual-cured, and placed in a cavity with a C-factor of 0 or 25. The influence of these variables on the cohesive strengths will be tested using a microtensile test. This study is described in chapter 2.

In chapter 3, the influence of surface pretreatment of fiber posts on cement delamination of three dual-cured resin cements will be tested using a three-point bending test. The fiber posts will be pretreated using silanization, sandblasting or a combination of both, with absence of pretreatment in the control group.

In chapter 4, a two-step cementation procedure for prefabricated fiber posts will be studied. This two-step cementation procedure is designed similar to the layering technique in composite restorations, in order to reduce the C-factor in the post space, thereby diminishing the polymerization contraction stress resulting in a stronger and more reliable bond between post and dentin. This procedure will be tested with the same cements as used in chapter 3, and the conventional cementation procedure will be used as a control. The bond strength of the cement will be determined using a push-out test.

In chapter 5 a finite element analysis (FEA) will be carried out to determine the stresses present when cementing a fiber post using the conventional cementation procedure and the two-step procedure as described in chapter 4. The complete root with a post cemented in it and the push-out specimens as used in chapter 4 will be used to create finite element models.
In chapter 6, the aim is to evaluate the shear bond strength to bovine root dentin of three dual-cured resin cements cured in self- and dual-cured curing modes, and applied in bulk and in a thin layer in vitro. The forces present in the samples during testing will be investigated using finite element analysis. Apart from that, the volumetric shrinkage and polymerization contraction stress in self- and dual-cure modes of the cements will be determined.

The last specific aim of the thesis is to investigate the success and survival of indirect resin composite crowns during a three-year prospective clinical study. The crowns will be manufactured with a new resin composite material (NECO), and cemented with either one of two different luting cements. A distinction will be made between restorations cemented with different cements, and restorations in teeth with or without previous endodontic treatment. This study is described in chapter 7. Finally, the thesis will be summarized in English and Dutch.
References


Chapter 1


Pjetursson BE, Bragger U, Lang NP, Zwahlen M. Comparison of survival and complication rates of tooth-supported fixed dental prostheses (FDPs) and


