

Varying 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) level improves polymerisation kinetics and flexural strength in self-adhesive, remineralising composites

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Conflicts of Interest: Author Anne Young has, with Paul Ashley, had funding from NIHR and EPSRC. In the future, A.Y., inventor of the following patents: **Formulations and composites with reactive fillers (US8252851 B2, EP2066703B1, US20100069469, WO2008037991A1)**, and **Formulations and materials with cationic polymers (PCT/GB2014/052349, WO2015015212 A1, EP3027164A1, US20160184190)**, may receive royalties if a commercial product is produced. The team is currently working with Schottlander Dental Company to aid CE marking of a similar product to those in this publication.

Antonio Delgado received funding through PhD Grant SFRH/BD/136406/2018 supported by Fundação para a Ciência e Tecnologia (FCT), Portugal.

ABSTRACT

Objectives: To assess the influence of systematically varying concentrations of 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) versus 3% 4-META on the polymerisation kinetics and shrinkage, biaxial flexural strength (BFS) and modulus of remineralising composites.

Methods: Composites were prepared by adding poly(propylene glycol) dimethacrylate (24 wt%), camphorquinone (1 wt%) and MDP (0%, 5%, 10%, 15% and 20 wt%) or 4-META (3%) to urethane dimethacrylate. These were mixed with glass fillers containing 8 wt% monocalcium phosphate and 4 wt% polylysine (powder-liquid ratio of 3:1). Continuous spectral changes, following 20 s light exposure (37°C), were assessed with an ATR-FTIR to monitor polymerisation kinetics ($n=3$). Final extrapolated conversions ($D_{C,max}$) were employed to calculate polymerisation shrinkage. BFS and modulus of 24-hour dry stored disc specimens (10x1 mm; $n=10$) were determined using a ball-on-ring jig setup.

Results: Maximum rate of polymerisation and $D_{C,max}$ increased linearly from 2.5 to 3.5% s^{-1} and 67 to 83%, respectively, upon increasing MDP from 0 to 20 wt%. Values with 3% 4-META were 2.6% s^{-1} and 78%. Shrinkage was $3.8\pm 0.3\%$ for all formulations. Raising 4-META or MDP from 0 to 3 versus 5%, respectively, increased strength from 106 to 145 versus 136 MPa. A decreasing trend with higher MDP concentrations was noted. Elastic modulus showed no specific trend upon MDP increase.

Significance: Whilst final conversion levels were enhanced by 3% 4-META or >5% MDP, trends did not correlate with strength. Peak strengths with 3% 4-META or 5% MDP may therefore be due to acidic monomers providing linkage between the hydrophilic, non-silane treated particles and the polymer matrix.

Keywords: 10-MDP, degree of conversion, flexural strength, photopolymerization, self-adhesive composite

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Abbreviations:

10-MDP – 10-methacryloyloxydecyl dihydrogen phosphate

4-META – 4-methacryloyloxyethyl trimellitate anhydride

CI – confidence interval

Phenyl-P – 2-methacryloyloxyethyl phenyl phosphoric acid

PPGDMA – poly(propylene) glycol dimethacrylate

UDMA – urethane dimethacrylate

1. Introduction

Self-adhesive composites were introduced more than 10 years ago and are yet to achieve clinical breakthrough in current practice [1]. Perhaps the major drawback of self-adhesive composites is their limited interaction with dentine and consequently insufficient bond strength in cavity configurations which lack retention [2,3]. In addition, unacceptable longevity has been reported in clinical trials and laboratory studies previously conducted [4–6].

Self-adhesive composites rely on functional acidic monomers, which upon interaction with dentine, demineralize its surface and expose minerals that serve as sites for chemical bonding, following the adhesion-decalcification mechanism theory [7–9]. This bond differs according to the chemical structure and purity of each monomer and its affinity towards hydroxyapatite [10,11]. They should be able to etch and infiltrate simultaneously [2] and should have both hydrophilic and acidic components which gives the composite its self-adhesive properties. Levels, however, require optimisation to ensure they do not detrimentally affect monomer conversion, shrinkage and mechanical properties [10,12,13].

10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) is a monomer commonly used as an adhesion promoter in contemporary adhesives and luting agents. It displays self-etching potential that is well documented in the literature and the ability to form a stable calcium salt with hydroxyapatite [14–16]. It is widely regarded as the current best readily available functional monomer in dental adhesive technology [1,11,17–19]. It has also been included in the formulation of the self-adhesive commercial composite Constic (DMG, Germany) [5]. 10-MDP is a molecule characterized by two functional group: a phosphate group that makes it bondable to mineral apatite and a co-polymerizable methacrylate group, separated by a large spacer chain. This structure confers the desired hydrophobicity and also stability towards degradation when compared to other functional monomers that have shorter spacer chains or different chemical groups, such as 4-META or Phenyl-P [10,20,21]. The hydrophobic chain in 10-MDP facilitates

hydrophobic interactions with collagen, forming an aggregate that is stable and bound to the organic part of dentine [22].

The design of material formulations with further functional properties has been one of the latest developments in adhesive dentistry [23,24]. Calcium phosphate (CaP) particles intended to promote remineralisation of dental substrates, are being included in novel experimental materials [25]. Monocalcium phosphate is one of these particles. This has been included in the recently commercially manufactured, self-adhesive, remineralising composite, Renewal MI (Schottlander, UK). Such CaPs are generally not functionalized, unlike typical dental glass fillers which have a surface silane coupling agent. Consequently, CaP usually have no filler/matrix interface bonding which is required to ensure high strength and modulus [25]. In Renewal MI, addition of 4-methacryloxyethyl trimellitate anhydride (4-META) as a functional monomer to the liquid monomeric phase may provide this role. 4-META low solubility in Renewal MI monomer phase, however, makes 3 wt% its maximum concentration. The addition of MDP into a composite containing CaPs may, however, also promote this bonding due to ionic interaction of its phosphate group to the calcium in CaP particles used in the filler phase, which warrants research.

For the composite to achieve optimal physico-chemical properties, it is crucial that its monomer phase should undergo sufficiently rapid and high degree of monomer conversion (D_c) [26,27]. Suboptimal polymerisation affects stability of the set material and of the interface formed with the adhesive, ultimately impacting the longevity of the restoration [28–30]. Increasing the level of monomethacrylates also increases linearization of the polymer, affecting properties such as hardness, flexural strength and fracture behaviour. Thus, the monomeric system and ratios have been proven to directly impact polymerisation kinetics and mechanical performance of composites [31]. Optimisation of monomer ratios in self-adhesive formulations is then required.

The null hypotheses are that (1) maximum polymerisation rate and degree of conversion, (2) the associated calculated polymerisation shrinkage or (3) the biaxial flexural strength and elastic

modulus are not affected by the addition of 3% 4-META or higher levels of MDP (0-20%) within the monomer phase. Additionally, these properties show no systematic trends upon increasing the concentration of 10-MDP, in 5% increments, up to a terminal concentration of 20%.

2. Materials and Methods

2.1 Materials

MDP monomer was commercially obtained (DM Healthcare Products, California USA; P01030), and stored at 4°C. Experimental composites with varying amounts of this functional monomer were prepared, using a powder-to-liquid ratio of 3:1 (weight ratio). The liquid phase was mixed by combining urethane dimethacrylate (UDMA) (DMG, Germany; 100112/97406) with 24 wt% poly (propylene glycol) dimethacrylate (PPGDMA) (Polysciences, USA; 626208). Either 0, 5, 10, 15 or 20 wt% 10-MDP and 1 wt% camphorquinone (CQ, Polysciences, USA; 100134/90339) were included (see Table 1). MDP was fully soluble in the monomer mixture, at all concentrations.

Table 1. Ratios of the components in the monomer phase of the experimental formulations. 1

wt% CQ was also added to each formulation.

Formulation	UDMA (wt%)	PPGDMA (wt%)	10-MDP (wt%)
MDP0	75	24	0
MDP5	70	24	5
MDP10	65	24	10
MDP15	60	24	15
MDP20	55	24	20
Renewal MI	72	24	3*

*4-META was added to Renewal MI, not 10-MDP

The powder phase was made up of hybrid barium silicate glass fillers of 7 μm , 0.7 μm (DMG, Hamburg, Germany) and nano fumed silica (Aeorosil OX50, Evonik Industries, Essen, Germany – 1532022145) combined at a 6:3:1 weight ratio. To this, 8 wt% monocalcium phosphate monohydrate and 4 wt% polylysine particles were added. These may promote remineralising, self-sealing and antibacterial features in resin-dentin interfaces [32,33]. Powders were mixed at 1000 rpm for 30 s using a Speedmixer (DAC600.2 CM51, Synergy Devices Ltd). The liquid phase was added to the powder in plastic pots, at a 3:1 powder to liquid ratio, and mixed without vacuum at 2300 rpm for 15 s. By mass, the final composite percentages of glass fillers, silica, monocalcium phosphate, polylysine, and liquid phase are 59.4, 6.6, 6, 3 and 25 wt% respectively. Assuming pure component densities of 2.8, 2.0, 2.2, 1.25 and 1.10 g/cm^3 gives the volume percentages as 40, 6.3, 5.2, 4.5 and 44 vol% respectively.

For comparison purposes, a self-adhesive, remineralising formulation developed at UCL Eastman Dental Institute was prepared. This formulation is licensed to Schottlander (Renewal MI, Davis, Schottlander and Davis Dental Company, Letchworth, UK), has been commercially full-scale manufactured and is currently undergoing clinical trials. It has an identical composition, to the formulations described above except that 4-META is present at its solubility limit of 3 wt% instead of any MDP. Renewal MI filler phase is also identical to the experimentals described above, including monocalcium phosphate and polylysine levels. The relatively high level of CQ in Renewal MI makes the formulations initially yellow. However, 20s light exposure enables efficient photobleaching and shade change from B2 to B1 (VITA classical scale), determined using a spectrophotometer (Spectroshade Micro Optic, MHT, Italy), using the CEILAB scale, of both top and lower sample surfaces.

2.2 Polymerisation kinetics and shrinkage

To determine polymerisation kinetics, a temperature-controlled diamond tip Attenuated Total Reflectance Fourier Transform Infra-Red (ATR-FTIR) system was employed (ATR, Specac Ltd,

Orpington, UK; FTIR Spectrum One Perkin-Elmer, UK). Metal circlips (2 mm thickness x 10 mm diameter) placed around the ATR diamond were used to contain the experimental composite pastes, and an acetate sheet was placed on top. The top surface of the material was irradiated with a single emission peak light emitting diode (LED) light curing unit (Demi Plus, Kerr, Orange, CA, USA), with a wavelength range between 450-470 nm, in direct contact with the acetate. The power output value was 600 mW/cm², as was measured with an analog radiometer (Demetron Dental Curing Radiometer model 100, Demetron Research Corp., Danbury, USA). FTIR spectra were obtained for 20 s before, during and after 20 s of light exposure. Spectra were acquired from 700 to 4000 cm⁻¹ at a resolution of 4 cm⁻¹, for 20 minutes at 37°C (Spectrum One with Timebase software v. 3.4.1, Perkin-Elmer, MA, USA). The light curing began, on average, 20±5 s after the start of spectral acquisition. Monomer conversion versus time (D_C) was calculated using the following equation:

$$D_C (\%) = [100(h_0 - h_t)]/h_0 \quad (1)$$

Where (h_0) and (h_t) are the methacrylate C-O stretching peak absorbance at 1320 cm⁻¹ above background at 1335 cm⁻¹ initially and at time t after the start of polymerization initiation, respectively. Obtaining spectra continuously during polymerization without any disconnect from the ATR diamond enables continuous monitoring of the same material volume during polymerization. This removes the need for normalization by a reference peak. The validity of this method has been verified previously in a wide range of studies [34–36]. From the data resulting from the non-irradiated bottom surface layer, maximum rates of polymerisation were determined, and final D_C extrapolated using multiple data points. The maximum rate of polymerisation ($R_{p,max}$), or reaction rate, during light exposure was calculated using the first derivative of the D_C versus time curve and is shown in %/s. Once the light is turned off, a dark cure phase begins, where the polymerisation reaction may continue for many hours, at an ever-decreasing rate [37]. During this period, degree of conversion versus inverse time plots were found to be linear with r^2 values close to 1. As inverse of zero is infinity, the intercept on the y axis of straight lines through a large number of later time data points, versus inverse time, could therefore provide the potential final level of conversion $D_{C,max}$ with a high degree of confidence.

In methacrylates, the volumetric shrinkage-strain is mainly caused by the conversion of C=C monomers during polymerisation. One mole of polymerising C=C bonds gives 23 cm³ of volumetric change. Due to this, a semi empirical relationship can be derived, and the following equations can be used to calculate volumetric polymerisation shrinkage [38,39], if the filler load, mass fraction of each monomer and degree of conversion are known:

$$N = m_t D_{C,max} \rho \sum_i \left(\frac{n_i \times x_i}{W_i} \right) \quad (2)$$

N represents the number of moles reacting per unit volume (mole/cc), m_t is the total monomer mass fraction and $D_{C,max}$ the final monomer conversion of the material. Σ indicates a sum over all the monomers in the liquid phase with n_i their number of C=C bonds per molecule, x_i the monomer mass fraction in the liquid phase and W_i the molecular weight of the monomer (g/mole). ρ is the density of the material (g/ cm³). This can be estimated assuming

$$\frac{1}{\rho} = \sum_i \left(\frac{m_i}{\rho_i} \right) \quad (3)$$

Where m_i and ρ_i are the mass fraction and density of each pure component in the composite.

Once N is known, polymerisation shrinkage, P_s (vol%), is estimated using the equation:

$$P_s = 100k_v N \quad (4)$$

where the constant, k_v (23 cm³ /mol) is the volumetric contraction upon polymerization of 1 mole of a methacrylate monomer.

2.3 Biaxial flexural strength and elastic modulus

Biaxial flexural strength was also evaluated to compare the mechanical properties of the five different formulations and the influence of different percentages of 10-MDP, following the protocol of previous studies [38,40]. Resin composite disc specimens were made ($n=10$ for each formulation) by dispensing the material into metal circlips (1 mm thickness x 10 mm diameter) with acetate sheet placed to seal the top and bottom. Discs were subsequently polymerised according to ISO 4049:2019, in 4 overlapping circles on the top and bottom surface, for 20 s each, to guarantee complete polymerisation. An LED curing unit with the parameters described above was used (Demi Plus, Kerr, Orange, CA, USA). Discs were stored dry for 24 h, at room

temperature, prior to the flexural strength measurement. Discs were placed on a knife-edge support ring (8 mm diameter) and the load was applied (2 kN load cell), using a ball-on-ring setup, with a spherical ball indenter (4 mm diameter) at a crosshead speed of 1 mm/min (Shimadzu AGS-X, Kyoto, Japan). The maximum force at failure (in N) was recorded and the biaxial flexural strength, expressed in MPa, was calculated using the following equation [41]:

$$S = F/t^2\{(1 + \nu)[0.485 \ln \times (e/t) + 0.52] + 0.48\} \quad (5)$$

where F represents the load applied at failure (in N), t is the specimen thickness, e is the radius of the support ring and ν is the Poisson ratio (0.3). Using the force versus displacement graph, it was possible to calculate the biaxial modulus of elasticity using the equation:

$$E = (\Delta J/\Delta Wc) \times (\beta_c e^2/h^3) \quad (6)$$

where E is the elastic modulus of the composite, expressed in GPa, $(\Delta J/\Delta Wc)$ is the gradient of force versus the displacement curve, β_c is the center deflection function and center deflection junction (0.5024), h is the ratio of the support ring radius to the radius of the disc, and e is the radius of the support ring.

2.4 Statistical analysis

Statistical hypothesis testing to investigate the effect of different concentrations of MDP on polymerisation kinetics (maximum rate of polymerisation, final degree of conversion), volumetric shrinkage and biaxial flexural strength were conducted with an ANOVA one-way for the comparison of means, using SPSS v.26 (IBM, USA). However, the elastic modulus medians were analysed using a Kruskal-Wallis H Test as they did not meet parametric assumptions. Post-hoc multi-comparison tests included Tukey's HSD and Dunn's test for Kruskal-Wallis. All inferential analyses were conducted at a significance level of 5%. Linear regression fits were performed using Origin(Pro) Version 2021 (OriginLab Corporation, Northampton, MA, USA), using instrumental weighing to take into account standard errors. Graphing reports the linear fit and 95% confidence band. Sample sizes were calculated using G*Power 3.1 for Mac, for a power of

80% and alpha error probability of 5%, by estimating the effect size from D_c (%) means and biaxial flexural strength, based on results of a pilot study undertaken when comparing preliminary experimental groups.

3. Results

3.1 Polymerisation properties

D_c (%) versus time, for the different formulations, is shown in Figure 1. Findings show 20 s curing was sufficient to achieve high levels of conversion. In all cases, there was rapid reaction, as the light was turned on, that slowed abruptly soon after light curing ended. Conversions achieved before the reaction slowed significantly are provided in Table 2. Also provided are calculated mole percentages of methacrylate groups due to MDP or 4-META in each formulation. Mole percentage of polymerising groups from dimethacrylates will be 100 minus the monomethacrylate percentage. The level of conversion required to join all the monomer molecules (assuming no crosslinking), equals half this dimethacrylate percentage plus the monomethacrylate mole percentage. As can be seen from Table 2, this conversion is comparable to that achieved before substantial reaction rate reduction for all formulations, except for MDP5 and Renewal MI. Whilst MDP5 reaction slows at conversions below the critical minimal level required for all monomers to be joined, with Renewal MI there is significant crosslinking before the reaction slows.

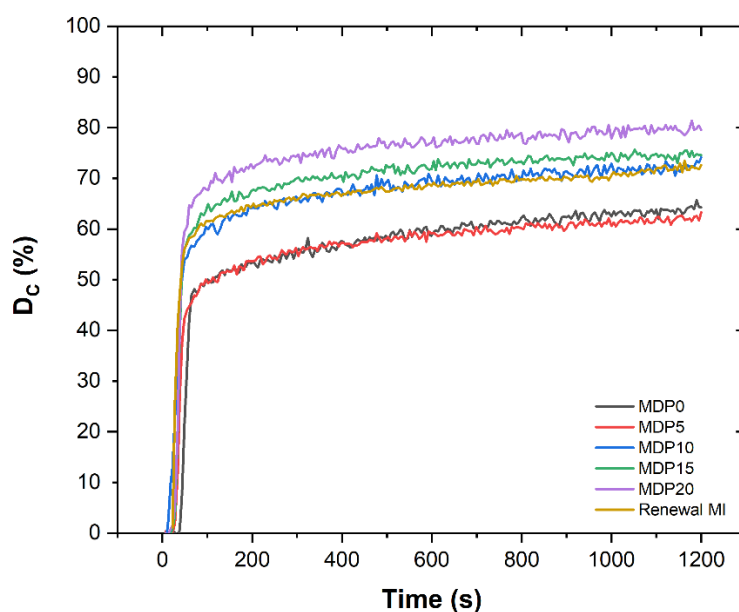


Figure 1. Conversion kinetics shown, over time, up to 1200 s (20 minutes), mean of real-time conversion data ($n=3$). Light curing began 20 ± 5 s after start of data acquisition and lasted for 20

s. Findings show an increasing trend of D_c (%) upon increasing levels of 10-MDP. Conversion at 200 s is typically ~90-95% of the final extrapolated $D_{c,max}$ values. Conversion reaches values close to 50% before slowing down, in the fast reaction phase for 0-5% MDP, whereas for 10-20% MDP, conversion reaches values around 60%. Renewal MI results were comparable to 10% MDP. In this rapid reaction phase, monomers are expected to join together in linear chains.

Further changes, when the reaction slows down, are likely due to crosslinking.

Means and standard deviations for each formulation, of $D_{c,max}$ (%), $R_{p,max}$ (% s⁻¹) and calculated maximum shrinkage (vol%) are also shown in Table 2. Whilst the $D_{c,max}$ (%) was significantly increased by 3% 4-META addition, the other two properties were not. Final degree of conversion was MDP concentration-dependent (one-way ANOVA, $p < 0.001$, $\eta^2 = 0.94$), as were $R_{p,max}$ (one-way ANOVA, $p = 0.008$, $\eta^2 = 0.72$) and shrinkage (one-way ANOVA, $p = 0.001$, $\eta^2 = 81$). An increase in the concentration of MDP increased D_c (%) and $R_{p,max}$. As for shrinkage, formulations demonstrated comparable changes in vol% except for 10% MDP, which had a small but statistically significant increase compared to other formulations (Tukey's HSD, $p \leq 0.05$).

Table 2. Means (SD) of the extrapolated $D_{c,max}$ (%), $R_{p,max}$ (% s⁻¹) and calculated polymerisation shrinkage (vol%) ($n=3$). Different capital letters in the same column indicate significant differences (Tukey's HSD, $p \leq 0.05$). Table also shows mol% of methacrylate groups corresponding to MDP/4-META within each formulation, the D_c (%) at which the polymerisation rate slowed down and the expected D_c (%) after all monomers are joined. The latter was calculated by adding the MDP/4-META mol% of total methacrylate groups to half that from the dimethacrylates.

MATERIAL	MDP/4-META contribution to methacrylate groups (mol%)	D _C expected after initial chain formation (%)	D _C at which reaction slowed (%)	D _{C,max} (%)	R _{p,max} (%s ⁻¹)	Shrinkage (vol%)
				Means (SD)	Means (SD)	Means (SD)
MDP0	0	50	49 (5)	69 (0.2) ^A	2.5 (0.4) ^A	3.7 (0.1) ^A
MDP5	4	52	43 (3)	65 (2) ^A	2.4 (0.1) ^{AB}	3.6 (0.1) ^A
MDP10	8	54	51 (2)	76 (2) ^B	2.9 (0.4) ^{ABC}	4.1 (0.1) ^B
MDP15	12	56	55 (2)	77 (3) ^B	3.3 (0.1) ^C	3.7 (0.2) ^A
MDP20	16	58	60 (2)	83 (1) ^C	3.5 (0.3) ^C	3.7 (0.1) ^A
RENEWAL MI	2	51	60 (2)	78 (1) ^B	2.6 (0.3) ^{AB}	3.5 (0.03) ^A

The relationship between the variables D_C (%) and MDP concentration was assessed through linear regression, showing a significant model (ANOVA model, $p=0.02$). R_{p,max} was also found to have a strong correlation with MDP concentration, (ANOVA model, $p=0.01$). The regression analyses are shown in Figure 2.

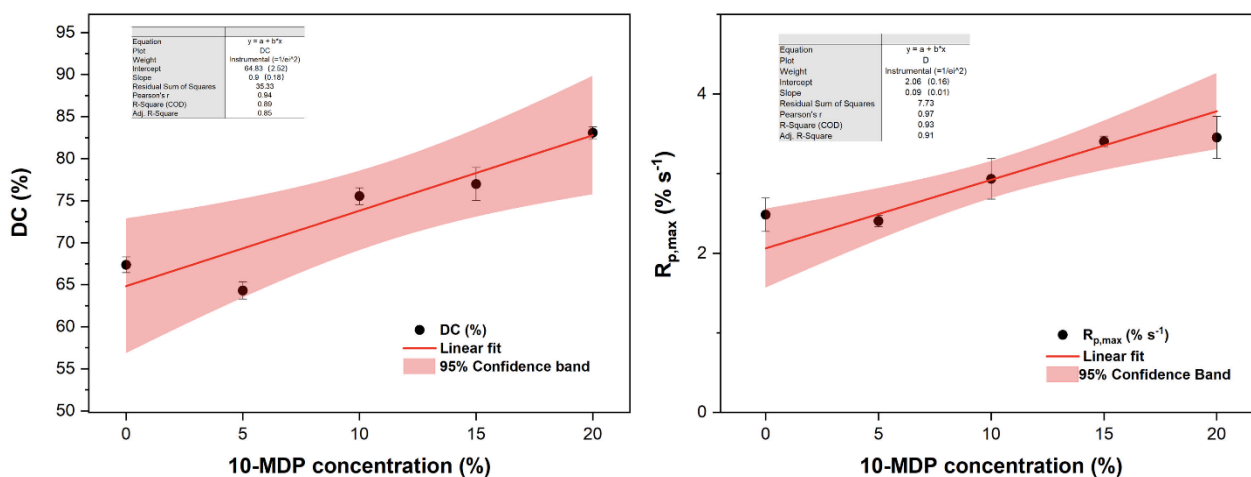


Figure 2. D_{C,max} (%) and R_{p,max} plotted versus MDP concentration in the monomer phase. D_{C,max} (%) was found to have a positive, linear correlation (Pearson's $r=0.94$) with 10-MDP concentration, as did R_{p,max} (% s⁻¹) (Pearson's $r=0.97$). Error bars shown are standard errors.

3.2 Biaxial flexural strength and elastic modulus

Biaxial flexural strength means and standard errors are shown in Figure 3. The MDP level influenced the biaxial flexural strength (ANOVA, $p < 0.001$).

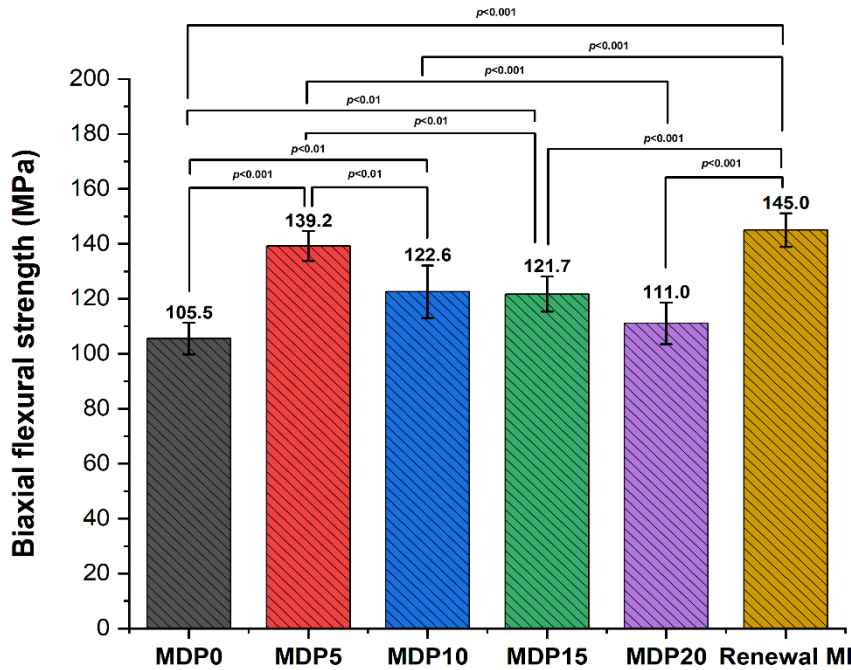


Figure 3. Means and 95% CI, in MPa, of the biaxial flexural strength across different formulations ($n=10$). Brackets indicate significant differences (Tukey's HSD post-hoc test, $p \leq 0.05$).

The formulation containing no monomethacrylates showed the lowest flexural strength (105.5 ± 8.0 MPa). Maximum biaxial flexural strength was seen with 3% 4-META (Renewal MI) (145 ± 7.6 MPa), followed by 5% MDP (139.2 ± 7.6 MPa), which then decreased with further MDP addition. The elastic modulus also showed differences between the materials (Kruskal-Wallis, $p < 0.001$) and was just under 5 GPa for all formulations (Figure 4), except for the MDP10 formulation. In this case, no specific trend was followed, although a higher modulus was attained at an intermediate concentration of 10% MDP (5.2 ± 0.4 GPa), after which it decreased at 15% (3.8 ± 0.2 GPa) and rose again at 20% (4.8 ± 0.2 GPa).

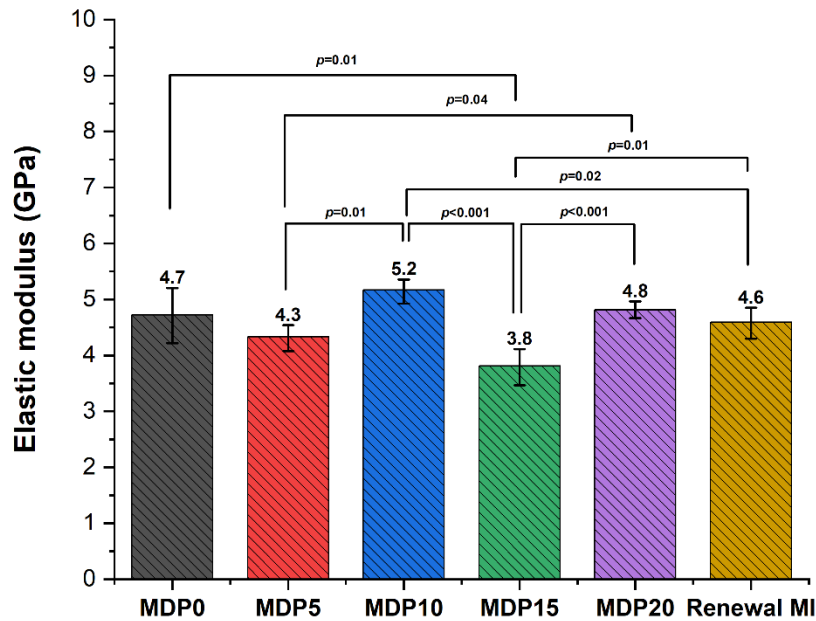


Figure 4. Means and error bars showing 95% CI (calculated using bootstrap estimates by resampling 10 000 x), of the elastic modulus, in GPa, across different formulations ($n=10$).

Brackets indicate significant differences (Dunn's post-hoc test, $p \leq 0.05$).

4. Discussion

The null hypotheses that maximum degree of conversion and biaxial flexural strength are not modified by addition of 3% 4-META can be rejected. 4-META effects on conversion rates, polymerization shrinkage and modulus, however, were not significant. All these properties, were significantly affected by higher levels of MDP, further rejecting the null hypotheses for 10-MDP. Conversion rates and final levels show linear trends with MDP level, but shrinkage and strength have peak values with 5 and 10% MDP respectively. Additionally, with modulus values there was no clear trend with MDP concentration. There was therefore no direct correlation between these properties.

In this study, the resin composite formulations tested were based on a UDMA/PPGDMA system, to which 1 wt% CQ was added. This relatively high initiator level enables fast reaction without any additional, potentially cytotoxic amine activator [33,40]. Poly-l-lysine was introduced as a

compound as it can potentially bind to collagen, enhance biomineralisation and has been shown to have antibacterial action in cariogenic-relevant bacteria [32,42]. To achieve remineralising properties, monocalcium phosphate particles were added. Levels of these components are being optimised, to promote sufficient water sorption, which can then enhance penetration of the resin phase into demineralised dentine.

Previously, 4-META was included in the UDMA/PPGDMA to further improve adhesion promotion in dentine. It was also proposed it might provide a bond between the monomer and these hydrophilic particles [32,43]. The increase in strength seen above with 4-META addition provides evidence that this interface bonding might be occurring. Higher strength could additionally, however, be a consequence of the observed greater monomer conversion. Trends with acidic monomer concentration might help to further understand property variations, but 4-META solubility is limited (3 wt%). Consequently, in this study 4-META was also replaced by 10-MDP. This latter monomer has much greater solubility in the UDMA/PPGDMA monomer phase (>20 wt%), due to its longer aliphatic spacer group.

10-MDP is an alternative popular monomer, added to many dental bonding system formulations, due to its good adhesive properties and surfactant capacity [10,18,44]. Commercial dental adhesives have concentrations of MDP typically between 5 wt% to 15 wt% [45]. Within this range, adhesive properties can achieve their peak in both dental adhesives and self-adhesive resin cements. Whilst studies have evaluated the effect of different concentrations of this monomer on adhesive properties [46,47], its effects in more hydrophobic composites could be very different. Structuring and aggregation of this molecule is expected to have different effects on material properties. Since MDP is an amphiphilic molecule, in hydrophobic composites its hydrophilic domain is expected to interact with other hydrophilic interfaces (e.g., monocalcium phosphate and polylysine particles, or water on tooth surfaces), while the hydrophobic tail remains internal. Additionally, this monomer will turn the polymerised matrix phase into an ionic phase. Whilst in hydrophilic systems the ionic groups can ionize causing repulsions between chains, in

hydrophobic composites the ionic groups will tend to associate. This provides reversible ionic interactions between chains, which may break and reform in a dynamic manner under certain conditions [48]. MDP has been demonstrated to be able to self-assemble and associate into multiple bilayers on hydrophilic surfaces [44].

To study polymerisation kinetics, the ATR-FTIR technique was used. It enabled easy access for sample curing and simultaneous continuous monitoring of setting reaction kinetics [49]. The readings supply information on curing on the bottom, few micron thick, non-irradiated layer in contact with the ATR diamond [41]. Temperature control was important as reactions and D_C increase with temperature. Setting the ATR plate at 37 °C allowed better approximation to oral environment conditions.

Monomer flexibility, molecular weight, number of double bonds and intermolecular interactions (e.g. hydrogen bonding) are known to greatly affect reaction rates [40]. Monomethacrylate monomers such as 10-MDP can improve the final D_C levels, and concentrations higher than 5% may benefit this parameter, as suggested by previous authors, although tested in hydrophilic adhesives [50]. These monomers can only form linear polymer chains, and rely upon copolymerization with dimethacrylates, like UDMA or PPGDMA used in this study, to enable crosslinking [51].

To explain reaction rates and final D_C , understanding of reaction mechanisms is required. The free-radical addition polymerisation reaction in light-curable dental is well understood and may be described by five distinct steps, which are activation (1), initiation (2), propagation (3), termination (4) and crosslinking steps (5), respectively. The rate of each step equals the rate constant multiplied by the concentration of reactants. Crosslinking occurs when polymer chains have already formed - when a free radical reacts with a double bond on a polymer side chain. Steps 2-5 all require molecular diffusion which is determined by diffusion constants. According

to the Stokes Einstein (7) equation these are inversely related to the surrounding viscosity, η , and the molecular radius, R .

$$D = kT/6\pi\eta R \quad (7)$$

Where k is the Boltzmann constant and T is the temperature.

With respect to initiation, the yellow colour of CQ is responsible for high absorbance of blue light, while also yellowing the composite. Rapid photobleaching upon formation of free radicals allows the curing light to penetrate and initiate cure at greater depths, while also improving the colour of the composite [33].

With respect to the reaction rate, differences between the dimethacrylates and the monomethacrylates used should be considered. The rate of propagation is proportional to the concentration of monomer and total number of free radicals. With adding 20% MDP, the maximum reaction rate was increased by 40%. This reaction propagation rate is dependent upon the number of active site collisions and the likelihood that these will result in a reaction. As 10-MDP has a lower molecular weight compared to UDMA (10-MDP: 322.3 g/mol; UDMA: 470.6 g/mol), with similar densities (1.13 g/cm³) it has higher molar concentration (MDP 3.5 mole/L; UDMA 2.4 mole/L). Smaller molecules diffuse faster, giving higher number of collisions per second, that may result in reaction. Additionally, greater flexibility of the MDP molecule may enable faster reaction following collision, due to reduced steric hindrance effects [52]. Conversely, dimethacrylate monomers such as UDMA, with two reactive groups, have increased probability of the free radical collision site being close to a reactive methacrylate group.

At early reaction stages, the concentration of free radicals may be kept low by the termination step. As the reaction progresses, free radicals increase in size which consequently increases the viscosity of the mixture. Owing to this, radical diffusion is limited, and the termination reaction

slows down, while the reaction rate can rise sharply (Trommsdorff or gel effect). With larger and viscous dimethacrylate monomers, this gel effect can occur at lower D_C [53]. With higher concentrations of smaller, lower viscosity monomethacrylates, the gel effect is often delayed [54,55]. MDP, however, could have a complex effect on viscosity versus time and molecular diffusion rates due to possible interactions by the phosphate groups. These interactions may occur between MDP molecules, causing aggregation in the matrix bulk and at the hydrophilic particle surfaces [15]. For all composites, except 5% MDP, the reaction rate increased with MDP level, sufficiently for the increased numbers of monomer molecules to join before the light curing ended. The anomalously low $D_{C,max}$ of MDP5 could be a consequence of the majority of the MDP molecules being associated with the hydrophilic particles and therefore slower reacting, causing adverse steric effects.

Addition of monomethacrylates as co-monomers to a dimethacrylate mixture can enhance D_C levels, since they form only linear chains. The large size of the polymer molecules and therefore low molar concentrations and diffusion rates will cause the crosslinking reaction to be slow. With MDP this occurred largely after photopolymerization ended. Steric hindrance by the polymer chains may also inhibit free radical attack on the side chain methacrylate groups. The similarities in D_C expected with all monomers joining in linear chains and that when the reaction slows with MDP is consistent with crosslinking being much slower than the linear chain propagation step.

That 4-META was able to ensure significant crosslinking before the reaction slowed might be explained if it is more effective than MDP at reducing termination reactions at the hydrophilic particles surfaces. This might be a consequence of the 4-META anhydride group being highly reactive with any water in these particles particularly the monocalcium phosphate which is in the monohydrate form. Furthermore, its lower solubility than MDP in the monomers and likely increased insolubility following reaction with water might enhance its accumulation ability at hydrophilic surfaces.

Crosslinking will end with termination of all free radicals, or when the glass transition temperature (T_g) of the mixture equals that of the surroundings, turning it from a rubbery state into a glass [56]. Reduction of free volume and molecular movement takes place in this transition. Assuming all the molecules have at least one methacrylate group reacted, from the final extrapolated D_C of 69 versus 83%, with 0 and 20% MDP, 38 versus 59% of the second double bonds on the dimethacrylates have reacted. Higher crosslinking when MDP level is increased may be a consequence of it increasing the flexibility of the linear polymer chains due to it giving shorter side chains than UDMA. As seen by Yazdi and collaborators (2015), within adhesives, concentrations of 0 and 5% MDP achieve lower D_C than higher concentrations of this monomer [50]. Recently, varying concentrations of MDP and its effect on the D_C were also tested in zirconia primers [57]. Higher concentrations (>10 wt%) were found to affect the D_C , although this may be attributed to mixtures containing photoinitiator systems with amines. Acidic monomers can neutralize amines in an acid-base reaction, being responsible for a decline in polymerisation properties [58,59]. Thus, the present study may indicate that systems containing camphorquinone alone, polymerise well with functional monomers and should be preferred.

Ensuring all monomer molecules have reacted is critical to prevent possible elution of free monomer [41,60]. Additional crosslinking is also important to reduce water sorption, ensure good mechanical properties and enhance wear resistance. On another note, higher D_C rates are linked to better adhesive properties, which are relevant for self-adhesive features. Bond strengths to dentine may be enhanced through conversion-related strengthening and water-sorption reduction [27,61]. Furthermore, this study suggests 20 s light curing was enough to achieve good levels of D_C , in all formulations, for a 2 mm material thickness.

The calculated theoretical shrinkage method employed has shown to be well correlated with experimentally determined shrinkage recommended by ISO 17304:2013, proving itself as a useful and valid method [41,62]. Aljabo et al. (2015) found less than 0.5 vol% difference between values when the theoretical calculated method was compared to the experimentally determined, based

on the density measurements using the Archimedes principle, method. As the theoretical equation predicts, shrinkage-strain is generally directly proportional to final D_C [41,55] and inversely dependent upon monomer molecular weight. In fact, and as seen before, monomer composition explains the magnitude of the shrinkage-strain [63]. Changes owing to shrinkage when comparing the different formulations in this study are minor, as the lower molecular weight of MDP largely balances the increase in D_C that it causes. Lower concentration of methacrylate groups per unit volume in MDP (0.0035 mole/cc) compared to UDMA (0.048 mole/cc) being replaced are responsible for minimal variation between groups. Yet, when MDP concentration was 10%, shrinkage was higher, mainly due to sharp rise in the D_C (%). Standard deviations in this theoretical calculation arise from different D_C values inputted, based on the three repetitions measured using ATR-FTIR.

Since most restorations tend to fail due to tensile stresses, flexural strength is particularly important [64]. In this study, biaxial flexural strength was used, as it has strong correlation to more traditional three- and four-point bending flexural strength, with less variability [65,66]. High polymerisation levels are known to be important to ensure good strength. Considering the findings, the lack of correlation between polymerisation level and strength, however, suggests particle wetting and interaction effects with the matrix phase are taking place, and these may be particularly important in this study. Samples were stored dry in order to assess the effects of particle wetting without complications arising from water sorption.

The formulation containing no monomethacrylates had lower strength than formulations with 4-META, MDP or expected with a conventional composite. The addition of particles such as monocalcium phosphate and poly-L-lysine, which are non-functionalized and therefore cannot bond well to the resin phase is well known to be responsible for decline in mechanical properties of experimental composites [25]. In fact, marked reductions of biaxial flexural strength in dry discs after inclusion of calcium phosphate particles, alike in this study, have been well documented [33,67].

In resin cements, increase of 10-MDP previously had minimal effect on flexural strength. Polymerisable surfactants such as MDP, however, may aid wetting of the hydrophilic particles used in this study. In fact, MDP has a track record of excellent affinity to CaPs and can also phosphorylate collagen, hinting that it may also be interacting with poly-l-lysine [9,20,52]. Interestingly, as nanolayering phenomena have been described with hydroxyapatite, the same effect may take place in the bulk of the composite, to the monocalcium phosphate [45,68]. This nanolayer may be critical in providing a stable interface between filler-resin matrix. Such hydrophilic ionic interactions can therefore reduce air pockets, eliminating polymerisation inhibiting oxygen layers. It may also improve mechanical properties through bonding for particles to the organic matrix phase. This explains the rise in biaxial flexural strength with the addition of 3% 4-META and at 5% MDP. With 10-MDP, below this percentage, the surface effect required for particle interaction may have already been covered, meaning there may exist an optimal level for such benefit, which requires further research. This optimal level may have been reached with 3% 4-META which also has capability to bond to calcium phosphates due to its carboxylic acid groups in its acidic, active form, and specifically bond to MCPM, as was verified experimentally before [69].

Mechanical properties such as strength and stiffness are essentially related to the filler and the coupling agent of the composite [70]. Past studies have proven functionalization strategies to be of great importance to achieve filler interfacial bonding, with silanization being an example [71,72]. Low levels, in the range of 1-2% are required for this surface effect. The benefit of adding MDP for this effect may also be concentration-dependent. Just enough may be able to provide a layer compatible with good surface effects (alike Renewal MI, with 3% 4-META), whereas concentrations above 5% may provoke thickening of these layers, with association of multiple MDP molecules. Such interaction effects and decline in strength owing to formation of multiples layers, has been documented with silane. Consequently, similar effects may be taking place with the phosphoric acid ester

MDP in lower concentrations seems to promote a reinforcing effect which might be due to a homogeneous distribution, positively contributing to the polymer matrix architecture. However, in higher concentrations, agglomerates of linearized molecules form, resulting from the MDP molecules colliding with each other with increased D_C , ultimately serving as a weak point in the resin [73]. Modulus values experienced a decrease upon low level UDMA replacement by MDP. This may be a consequence of MDP lower rigidity. There is however an increase in modulus values when MDP concentrations reach 10%, which might be explained by the sudden increase in D_C . Conversion has been reported to be strongly related to modulus [56,74]. A higher modulus is achieved with high D_C values and hydrogen bonding capacity; however, these processes compete with each other. With hydrogen bonding there is restriction of molecular mobility, decreasing D_C , ultimately affecting modulus [75].

5. Conclusions

Adding 10-MDP to UDMA/PPGDMA self-adhesive experimental composites had a significant impact on the polymerisation kinetics and mechanical properties. Regarding polymerisation, MDP in increasing concentrations gave enhanced polymerisation rates, final conversion levels and crosslinking. Addition of 10-MDP and its impact on the calculated shrinkage is minimal as its higher molecular weight and methacrylate groups per unit of volume counterbalance the effect. Regarding biaxial flexural properties, 3% 4-META followed by 5% 10-MDP promoted the highest strength, while varying MDP levels had a complex effect on modulus. MDP may be a very interesting monomethacrylate co-monomer for resin composite formulations containing calcium phosphates and can be added in higher percentages in hydrophobic mixtures, in opposition to 4-META. These results suggest it may play a role in wetting the particles due to its ionic interactions, providing its own particle functionalization to the resin phase.

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